# DATA SHEET

### TR-1182

# Thermomechanical Properties of Beryllium

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## Note About Scope

This report reviews properties specified by the IAEA for Volume 5 of the Series "Atomic and Plasma-Material Interaction Data for Fusion". Other properties may be of interest to the fusion community, but they are beyond that specification. This review will focus where possible on measurements taken after 1979 with an emphasis on the properties of commercially available grades of beryllium block and ingot sheet.

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# THERMOMECHANICAL PROPERTIES OF BERYLLIUM

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## ABSTRACT

Beryllium is foreseen to be used as a cladding for plasma facing components and as a neutron multiplier in the tritium breeding blanket of a fusion reactor. Thermomechanical properties are presented for powder metallurgic and ingot sheet grades of beryllium that are commercially available. Additional characterisation under normal conditions is required for most grades of material particularly as regards Poissons ratio and fracture toughness at elevated temperatures. No radiation damage data has been found for a well characterised irradiation at any neutron fluence on a modern form of beryllium. Given the difficulties of obtaining fusion-relevant neutron spectra, it is suggested that even the effect of thermal neutrons on well-characterised beryllium samples, i.e. defined manufacturing method and impurity content would give valuable data on the behaviour of beryllium subject to neutron damage.

Most forms of beryllium presently considered for breeder blanket applications are porous forms and as such are not yet in a form that is commercially available.

## 1. INTRODUCTION

This review will summarise the properties of beryllium at temperatures of interest to application as a plasma-facing component (PFC) and in the breeder blanket. The principal advantages which Be has in PFC applications is its ability to getter oxygen and its low atomic number. These properties have been shown by experiment to eliminate density limit disruptions and to increase the time scale for magnetohydrodynamic instabilities [1]. It is now very likely that any future large tokamak fusion experiment will rely upon beryllium for PFC applications [2].

Like most metals, beryllium can be fabricated into a variety of forms such as block, sheet, rod, tube and wire. Historically, block has been of the most commercial interest and has been the most characterised form, however grades of beryllium developed recently have significantly improved properties. Beryllium ingot sheet will be another focus for this review as there has been recent assessment of a commercial product, and because its lower beryllium oxide content has provoked interest in the fusion community.

The primary use of beryllium in tokamak experiments [3, 4] has been for PFC which absorb heat without active cooling. In future experiments actively cooled beryllium clad heat sinks [5] or perhaps even directly cooled beryllium components [6] will be required to operate under steady-state conditions. Thus the experience gained so far with beryllium PFC is only a guideline for the design of actively cooled components. The requirements for a beryllium PFC for ITER are principally that the cladding remains intact and does not crack when subjected to $10^3$ cycles of long pulse ($10^3$s) steady state operation. This requirement is for the physics phase of ITER. The requirements for a later, engineering phase would require sustaining the same integrity for neutron irradiation of up to 2 dpa before replacement is required.

The cladding of beryllium to a copper heat sink, the latter being favoured for thermal reasons, intrinsically presents a problem in view of the formation of copper-beryllium eutectic at elevated temperatures and by the formation of brittle intermetallic compounds at lower temperatures [7]. Whereas there is some experience relating to the bonding of beryllium to heat-sinks, i.e. [8, 9], little published data has been found on the effect of fast neutrons on joints. One successful method of fastening, brazing, uses materials that are readily activated and which may be transmuted under neutron bombardment. The lifetime of PFC components may thus be limited by various considerations other than strength of the joint. Furthermore limitations arising from the joining technology may be more severe than the intrinsic limits of beryllium. Very considerable experimental work remains to be done in this field.

Beryllium is the material of choice as the neutron multiplier through (n, 2n) reactions in a solid breeder blanket design. Design optimisation studies [8] have shown that such a blanket, although based on lithium ceramics, would require up to 70% beryllium in order to maximise tritium production. The solubility and retention of hydrogen isotopes in beryllium both for PFC and for blanket applications under unirradiated and irradiated conditions is not fully understood. Widely scattered data have been presented for beryllium grades that are now obsolete. Furthermore new grades are at present being developed [11] which examine low density forms of beryllium that appear to have improved rates of desorption of tritium for use in breeder blankets.

Discharges in tokamaks using beryllium as wall and/or limiter material have produced encouraging physics results. Three different experiments, i.e. UNITOR, ISX-B and JET have relied upon beryllium material in the form of thick blocks. In many discharges however, plasma behaviour has been limited by a runaway accumulation of impurities due to loss of material from the PFC. In addition to the requirements for mechanical integrity, minimal deformation and resistance to large body forces during disruptions, the level of impurities within beryllium for fusion PFCs must be very low. In particular the presence of impurities with high atomic number must be minimised. JET has used material with very small amounts of impurities with high atomic number, i.e. <100 ppm total for elements above Fe in the atomic table [12].

## 2. SCOPE

Good summaries of beryllium data for grades that are no longer being produced may be found in the Reactor Handbook [13] and in an excellent review by Pinto [14] of the properties measured prior to 1979.

This review will focus on measurements taken after 1979 with an emphasis on commercially available grades of beryllium block and ingot sheet. Block has been the form most widely used and is the best characterised form. However, the low BeO content and high ductilities of ingot sheet has provoked interest in these materials for fusion applications. It is intended in this review to highlight those properties which require substantial additional characterisation, in particular for irradiated material. It is noted that the ITER programme foresees a need to develop even more robust forms of beryllium.

## 3. BACKGROUND

Beryllium is an element with atomic number 4 and atomic weight of 9.012. It is a metal with a hexagonal close packed structure. Beryllium in structural applications is notable for a combination of stiffness and low density. Due to its low atomic number, beryllium transmits x-rays seventeen times better than an equivalent thickness of aluminium. Excellent reflectivity for infrared radiation is observed; commercial grades are up to 98.5% effective in the 8-12 micron range. Beryllium is used for neutron reflectors and as a neutron multiplier due to its high neutron scattering cross-section, low thermal neutron capture cross-section and high (n, 2n) neutron multiplication cross-section. It has a strong chemical affinity for oxygen. Like aluminium, beryllium has a protective oxide layer.

In aerospace and other applications beryllium has been used due to its low specific modulus, which means that distortion of components made out of beryllium is minimised with respect to applied stress. The combination of high specific heat, high thermal conductivity, low coefficient of thermal expansion with the structural properties given above makes beryllium components dimensionally stable under transient thermal loads [22].

Beryllium grades are brittle at room temperature and become ductile at elevated temperatures with maximum ductility reached typically at 400°C. The PFC beryllium component comprises cladding on an actively-cooled substrate. One important criterion for the choice of grades to be considered is the ductility at coolant temperatures, i.e. ~ 100°C. The fatigue lifetime of the cladding has to be maximised with respect to regular thermal cycling at strain rates of the order of $10^{-4}$/sec.

Table 1: Thermophysical properties of beryllium at 300K (unless noted).

| Property | Value | |
|---|---|---|
| Melting Temperature | 1289°C | (7) |
| Boiling point at 1 atm | 2470°C | (7) |
| Heat of Fusion | 1132 KJ/Kg | (7) |
| Heat of Vaporisation | 24770 KJ/Kg | (15) |
| Density | 1848 Kg/$m^3$ | (14) |
| Electrical resistivity | $\simeq 4 \times 10^{-8}\ \Omega - m$ | (16) |
| Thermal conductivity | 204 W/m/K | (17, 18) |
| Coefficient of thermal expansion | $11.5 \times 10^{-6}$/K | (19) |
| Specific heat | 1.85 KW-sec/Kg/K | (7) |
| Viscosity at 1556K | $\simeq 10^{-3}$ poises | (20) |
| Youngs modulus | $\simeq$ 311 GPa | (21) |
| 0.2% Yield Strength | $\simeq$ 270 MPa | (21) |

Beryllium, like many industrial materials, poses a health risk if mishandled. In its usual solid form, as well as for finished parts, and in most manufacturing operations, it is completely safe. However, breathing very fine particles may cause a serious lung condition in a small percentage of individuals. Risk can be minimised with simple, proven, and readily available engineering controls such as ventilation of operations producing fine dust. JET has operated safely with beryllium in large quantities and under conditions producing fine particles. Details of the JET safety experience are given in Appendix A.

## 4. TYPES OF BERYLLIUM MATERIAL

The mechanical properties of beryllium vary significantly from grade to grade and also are strongly dependent upon specific fabrication technology. This review considers those grades available in ingot or block form. One manufacturer offers structural, instrument and optical grades of material [23]. Cast and rolled material called ingot sheet offers low BeO content and greater ductility than powder sheet above 200°C [24].

In the course of writing this paper the authors became aware of recent publications concerning the thermomechanical properties of beryllium produced by countries of the former Soviet Union [25]. In this latter report a wide range of materials are described to be forged, cold worked, hot pressed and/or rolled. In view of the multi-lateral agreement on the design of the ITER project it is expected that more information on the commercial availability of beryllium grades from this source will be forthcoming. However, as there is no data at present on the reproducibility of these properties for quantities of at least several hundred kilograms no further reference will be made to this source of material without prejudice to the quality of beryllium manufactured there.

Further ongoing development is to be noted of the methods whereby beryllium powder is produced. In particular the availability of spherical beryllium powder with very low BeO concentration, circa 0.5wt%, may produce grades of interest to the design of fusion PFC. Spherical beryllium powder has been made by inert gas atomisation [26, 27] and centrifugal atomisation [28]. Both processes involve the break up and rapid cooling of a molten metal stream to form powder. This type of powder has only been made in limited quantities.

A glossary of terms now follows relevant to the manufacture of beryllium through powder metallurgical (PM) methods or through ingot metallurgy (IM).

## 4a Powder Metallurgy of Beryllium

### *4a.1* *Milling*

Production of most forms of beryllium begins with chipping of a vacuum cast beryllium ingot. Chips are then ground using one of three methods.

Attrition Grinding (AG) Chips are ground into powder between two grooved beryllium plates, one fixed and one rotating. Plate-shaped particles are produced which tend to align preferentially during powder consolidation steps, resulting in anisotropic mechanical properties. This technique is becoming obsolete.

Impact Grinding (IG) Beryllium chips are suspended in a stream of high velocity gas and then directed at a solid beryllium target. The blocky particles produced this way result in a less textured microstructure and more uniform properties in all directions than attrition milling. The largest volume of beryllium is made using impact ground powder.

Ball Mill Grinding (BG) Ball mill grinding is an expensive and time consuming process which produces extremely fine particles and a higher BeO concentration. This results in an extremely fine grained microstructure in the final product. This microstructure confers enhanced resistance to thermo-mechanical distortion. Typically beryllium grades produced this way are used for precision guidance components.

### *4a.2* *Atomisation*

Inert gas atomisation produces spherical beryllium powder particles in contrast to the angular or blocky particles produced by grinding. Atomised spherical powder (ASP) generally has half as much as BeO or less as the other beryllium powders. This technology has only recently been successfully applied to beryllium.

### *4a.3* *Powder Consolidation*

Cold Pressing (CP) Powder is fed into a steel die and then uniaxially pressed from the top and bottom. The cold pressed or green powder billet then goes to one of the hot consolidation processes, usually sintering. Cold pressing tends to yield anisotropic mechanical properties.

Cold Isostatic Pressing (CIP) Powder is fed into flexible rubber bags which are sealed and lowered into a water filled pressure vessel. Pressure is applied simultaneously from all directions (isostatically). The CIP billet then passes through one of the hot consolidation processes. Products made with a CIP step tend to have more isotropic mechanical properties than products produced with a CP step.

Vacuum Hot Pressing (VHP) Powder is poured into a vertical cylindrical die. Pressure is then applied from rams at the top and bottom of the die under temperature and vacuum. Mechanical properties are anisotropic; mechanical properties measured parallel to the pressing direction (longitudinal) are generally lower than properties measured perpendicular to the pressing direction (transverse).

Hot Isostatic Pressing (HIP) Loose powder or a CIP powder billet is placed in a steel can which is welded shut after degassing at elevated temperature. The sealed can is then placed into a pressure vessel where it is heated and then pressed from all directions simultaneously (isostatically) by argon gas. Simple shapes made by HIP have minimal anisotropy in mechanical properties. Complex near net shapes can be made by this technique.

Sintering (S) A CP or cold CIP billet is placed in a furnace and heated under vacuum. Diffusion of beryllium atoms produces bonding. Sintered products have a coarser grain structure than HIP products and show anisotropy in mechanical properties.

Extrusion Billets made by CP or CIP are generally used as input stock, although extrusion of loose powder has been done. The feedstock is put in a cylindrical steel can, and degassed at elevated temperatures. The can is then welded shut and heated in a furnace. The hot can is then extruded through a die by a ram. Extruded products have anisotropic properties; the properties in the ram direction (longitudinal) differ from those in material perpendicular to the ram direction (transverse).

### 4b Ingot Metallurgy

*4b.1* Cast This covers any process where molten beryllium is poured into a mould and solidified. Cast beryllium generally has very coarse grain size and a different distribution of BeO compared to powder metallurgy beryllium. The strength and ductility of cast beryllium is much lower than powder metallurgy beryllium but can be improved by cold working and hot working to a fine grain size. Rolling is at present the only practical method to produce a fine grain size in cast beryllium. The most pure forms of beryllium are prepared by casting and zone refining techniques.

*4b.2* Ingot Sheet This is beryllium sheet produced from cast beryllium by rolling. It is notable for low BeO content and more ductility in the in-plane direction above 200°C than powder metallurgy sheet. The properties of these grades are anisotropic. It has been suggested that the out of plane ductility of these grades may be higher than powder metallurgy sheet which has an out of plane ductility of < 1%.

### 4c Refining Processes

Beryllium can be refined using the same techniques as other metals, but zone refining and vacuum distillation are currently used the most.

*4c.1* Zone Refining A bar of beryllium is placed in such a way that a furnace moves axially along it. A very small molten zone is formed at one end of the furnace and impurities are driven into the liquid by thermodynamic forces. Very high purity beryllium with very large grain size is produced. There are no commercial scale facilities for beryllium zone refining.

*4c.2* Vacuum Distillation Beryllium is vaporised and separated from impurities by fractional condensation. A high purity, coarse grained product is produced.

### 4d Summary of Commercial Grades

Although beryllium is used in relatively small quantities compared to steel or aluminium, specific grades have been tailored for the major aerospace applications: structural, guidance instruments and optics. Grain size, impurity content, anisotropy and BeO content are the principal differences between these grades. A brief summary now follows of commercial grades.

**Table 2:** Commercially available structural grades of beryllium

| Material<br>Powder<br>Compaction | S-65B/C<br>IG<br>VHP | S-200-E(1)<br>AG<br>VHP | S-200-F<br>IG<br>VHP | S-200-FH<br>IG<br>HIP | S-200-FC<br>IG<br>CP&S | MSC-100<br>ingot<br>sheet | SR-200<br>AG<br>VHP Sheet |
|---|---|---|---|---|---|---|---|
| Composition | | | | | | | |
| Be, min % | 99.0 | 98.0 | 98.5 | 98.5 | 98.5 | 99.5 | 98.0 |
| BeO, max % | 1.0 | 2.0 | 1.5 | 1.5 | 1.5 | < 100 ppm | 2.0 |
| Al, max ppm | 600 | 1600 | 1000 | 1000 | 1000 | 1000 | 1600 |
| C, max ppm | 1000 | 1500 | 1500 | 1500 | 1500 | 1000 | 1500 |
| Fe, max ppm | 800 | 1800 | 1300 | 1300 | 1300 | 1500 | 1800 |
| Mg, max ppm | 600 | 800 | 800 | 800 | 800 | NS | 800 |
| Si, max ppm | 600 | 800 | 600 | 600 | 600 | 1000 | 800 |
| Other, max ppm | 400 | 400 | 400 | 400 | 400 | 100 | 400 |
| UTS-min MPa | 290 | 276 | 324 | 414 | 262 | 276 | 483 |
| typ - L | 372 | | 372 | 441 | 317 | | |
| typ - T | 397 | | 393 | 414 | 262 | | 345 |
| YS-min MPa | 207 | 207 | 241 | 297 | 172 | 138 | |
| typ - L | 251 | | 255 | 345 | 207 | | |
| typ - T | 251 | | 241 | 345 | 172 | | |
| % elongation - min | 3.0 | 1.0 | 2.0 | 3.0 | 2.0 | 3.0 | 10.0 |
| typ - L | 3.8 | | 4.0 | 4.9 | 4.1 | <1 | <1 |
| typ - T | 6.0 | | 6.0 | 4.9 | | <1 | <1 |

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(1) no longer commercially available

NS - not specified

Table 3: Commercially available Instrument and Optical Grades of Beryllium

| **Material** | **I-70** | **I-70-H** | **I-220-H** | **I-250** | **I-400** | **0-50** |
|---|---|---|---|---|---|---|
| **Powder** | **IG** | **IG** | **IG** | **IG** | **BG** | **IG** |
| **Compaction** | **VHP** | **HIP** | **HIP** | **HIP** | **VHP** | **HIP** |
| Composition | | | | | | |
| Be, min % | 99.0 | 99.0 | 98.0 | 97.0 | 94.0 | 99.0 |
| BeO, max% | 0.7 | 0.7 | 2.2 | 2.5 | 4.25 min. | 0.5 |
| Al, max ppm | 700 | 700 | 1000 | 1000 | 1600 | 700 |
| C, max ppm | 700 | 700 | 1500 | 1500 | 2500 | 700 |
| Fe, max ppm | 1000 | 1000 | 1500 | 1500 | 2500 | 1000 |
| Mg, max ppm | 700 | 700 | 800 | 600 | 800 | 700 |
| Si, max ppm | 700 | 700 | 800 | 600 | 800 | 700 |
| Other, max ppm | 400 | 400 | 400 | 400 | 100 | 400 |
| UTS - min MPa | 241 | 345 | 448 | 517 | 345 | 241 |
| typ - L | N/A | 503 | 634 | 606 | N/A | N/A |
| typ - T | N/A | 490 | 634 | 606 | N/A | N/A |
| YS - min MPa | 172 | 207 | 345 | 448 | N/A | 172 |
| typ - L | N/A | 338 | 542 | 524 | | N/A |
| typ - T | N/A | 338 | 542 | 524 | | N/A |
| % elong - min | 2.0 | 2.0 | 2.0 | 1.5 | N/A | 2 |
| typ - L | N/A | 5.1 | 3.7 | 3.0 | | N/A |
| typ - T | N/A | 5.1 | 3.7 | 3.0 | | N/A |
| Microyield (MPa)(1) | 12 | 21 | 41 | 69 | 62 | NS |

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(1) Stress required to produce $2.5 \times 10^{-2}$ mm permanent strain.

NS - not specified

Structural Grades (S-65, S-200-F, S-200-E, MSC-100, SR-200) are processed to provide the highest strength. They are the most versatile grades and are the most well characterised. Nominal properties of selected grades are shown in Table 2.

Instrument Grades (I-220-H, I-400, I-70) are designed to provide the least distortion in aerospace guidance instruments. They are optimised to provide the best micro yield strength which is the maximum stress which can be applied before one microinch of plastic strain is made. Nominal properties are shown in Table 3.

Optical Grades (0-50, I-70, I-220-H) are optimised for reflectivity and polishing characteristics. The principal application is for satellite mirrors, although there are some terrestrial mirror applications where weight and infrared reflectivity are important. Nominal properties are shown in Table 3.

The S-65 grade was originally chosen by JET for First Wall and Divertor applications because it combined low impurity level (for low plasma contamination) with low BeO content and superior ductility at elevated temperatures. However, in other applications where strength is the overriding factor, instrument grades are more appropriate. It should be noted that instrument grades have the highest BeO contents of the commercial beryllium grades, and often have higher impurity levels and lower ductility than the structural grades.

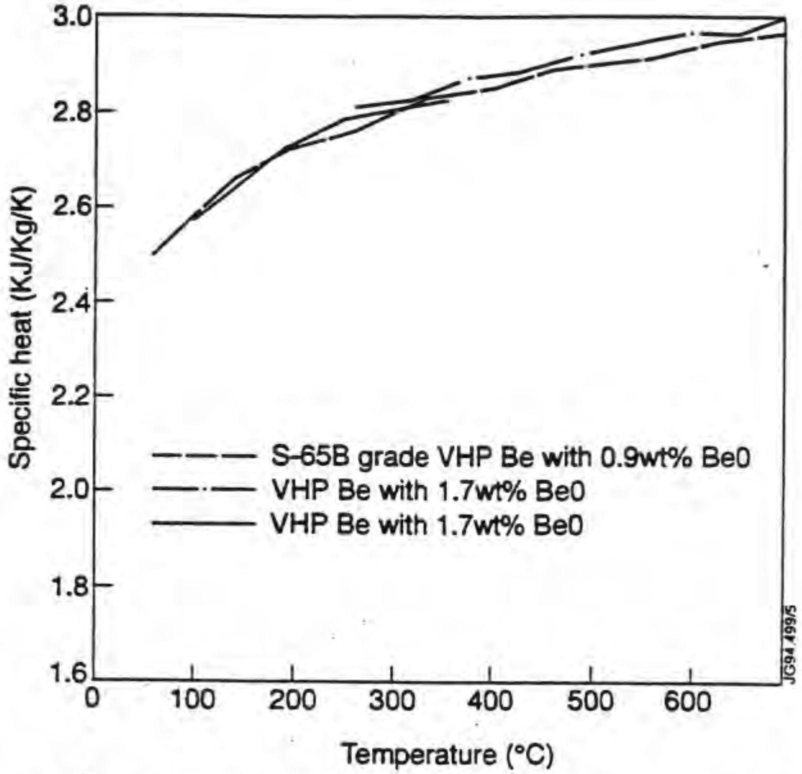
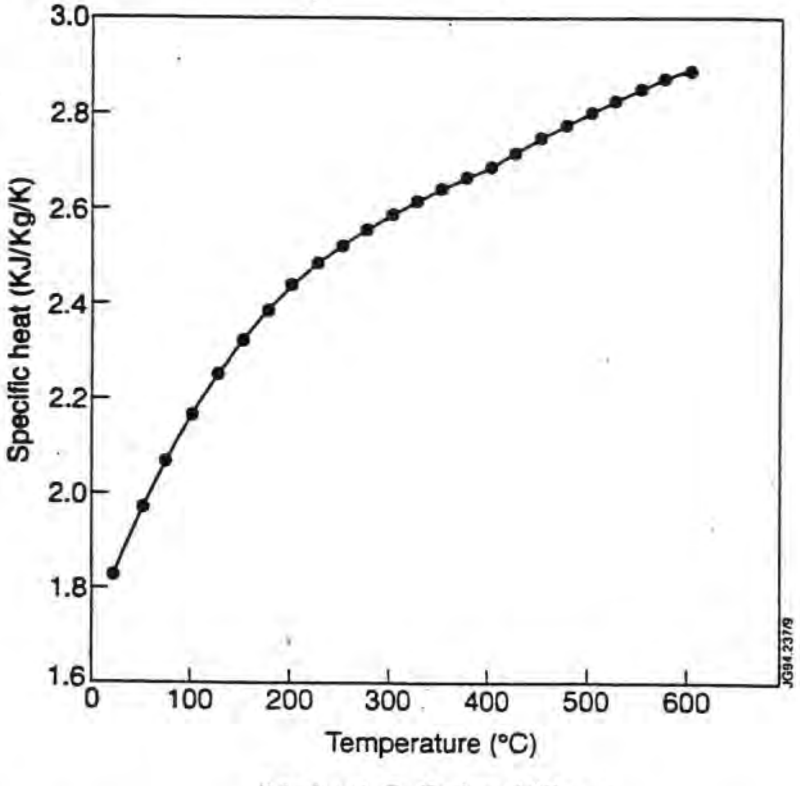


Fig. 1 Specific heat of VHP Be [16]. Specific heat of S-65B grade VHP Be [21].



IM sheet, BeO circa 100ppm

Fig. 2 Specific heat for IM Be [29] sheet with unknown BeO content [29].

## 5. BASELINE PROPERTIES

Many of the thermophysical properties of beryllium vary not only from grade to grade but also change substantially due to neutron irradiation. For example, yield strength, ultimate tensile strength and ductility are expected to be influenced substantially by radiation damage. These properties are discussed in detail in subsequent sections. This section presents data for those properties which are not expected to be influenced by neutron damage.

### 5a Specific Heat

Recently measurements of specific heat have been made of commercially available grades for which the fabrication process and the impurity levels have been given. In Figure 1 specific heat is plotted for (a) VHP beryllium with 1.70% BeO by weight [16] using adiabatic calorimetry, (b) VHP beryllium with 1.70% BeO by weight [16] using the slope of an enthalpy curve, (c) VHP beryllium grade S-65B with 0.8% BeO by weight [21]. Figure 2 shows data for IM beryllium sheet [29] for which the BeO content is likely to have been less than 100 ppm.

The specific heat of S-65 material as tabulated in Table 4 below is seen to vary between 17.2J/mole/K at 51°C to 29.0J/mole/K at 996°C. For ingot sheet specific heat range is 16.5J/mole/K at 23°C and 26.0J/mole/K at 602°C.

The specific heat of liquid beryllium is relevant in the assessment of material loss from PFC due to disruptive events that produce surface melting. Values of 3.27 KJ/Kg/K at melting temperature rising linearly to 3.45 KJ/Kg/K at boiling point have been reported [14]. It is not clear that this result would vary greatly from grade to grade unless the percentage of BeO varies greatly from the values of up to 2% typical of modern forms of beryllium.

### 5b Density

The density of any material varies with temperature as a consequence of thermal expansion. Variation of density with temperature is listed in Table 4 for commercially available VHP grade, S-65B beryllium with 0.9% by weight of BeO.

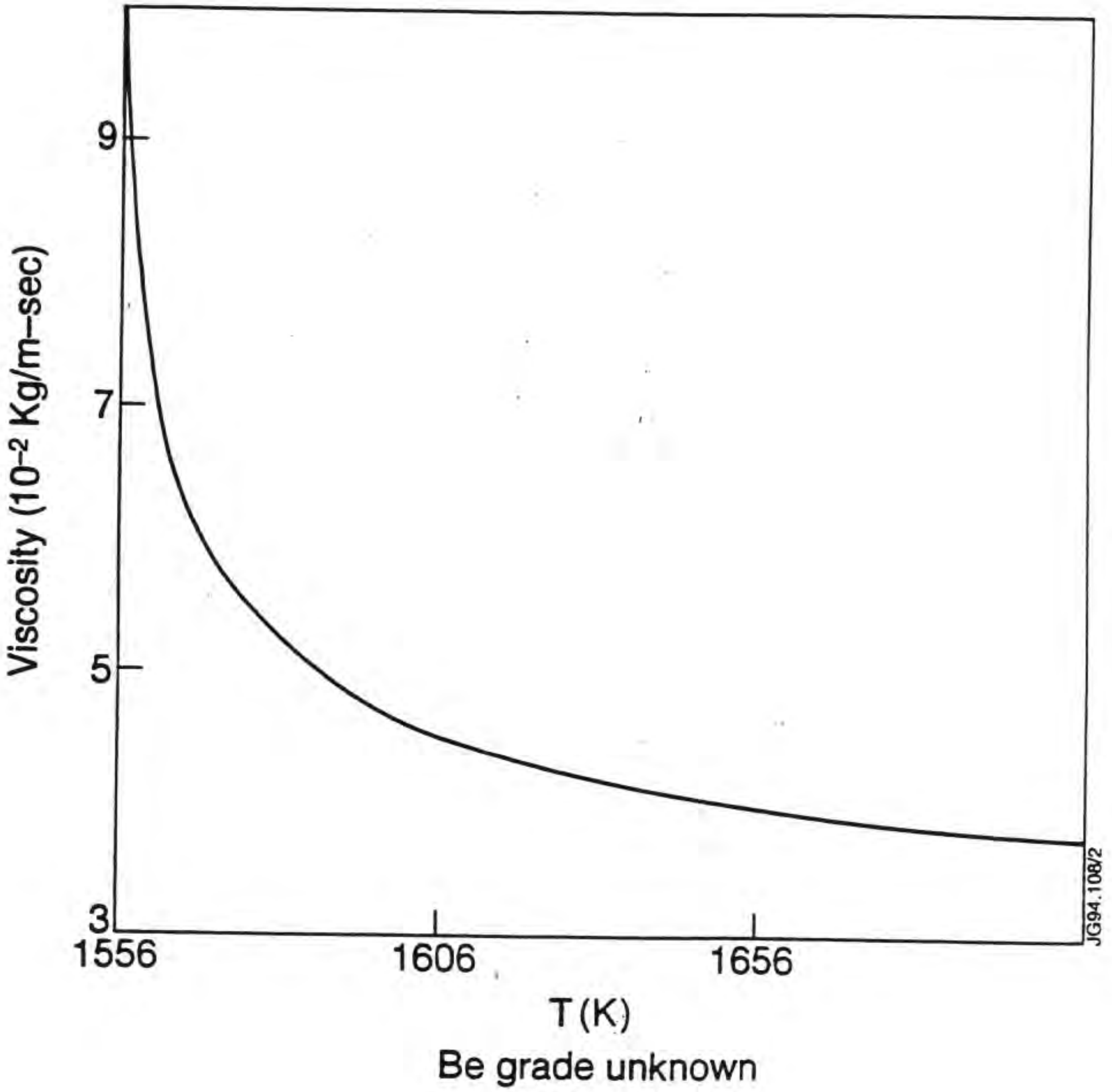


Fig. 3 Viscosity of molten beryllium [20]. The beryllium stock was 99.85 to 99.9% pure and had an unknown amount of BeO.

Table 4: Reference thermal properties S-65b [21]

| Temperature °C | Conductivity W/m/k | Specific heat KJ/Kg/K | Density $Kg/m^3$ |
|---|---|---|---|
| 51.0 | 187.3 | 1.905 | 1820 |
| 139.0 | 152.3 | 2.240 | 1814 |
| 183.0 | 143.8 | 2.344 | 1806 |
| 242.0 | 133.8 | 2.441 | 1806 |
| 291.0 | 128.8 | 2.529 | 1801 |
| 336.0 | 125.2 | 2.613 | 1797 |
| 400.0 | 116.6 | 2.667 | 1791 |
| 464.0 | 110.4 | 2.734 | 1785 |
| 543.0 | 101.8 | 2.780 | 1777 |
| 619.0 | 96.1 | 2.860 | 1769 |
| 700.0 | 88.4 | 2.939 | 1760 |
| 854.0 | 75.8 | 3.086 | 1742 |
| 996.0 | 63.8 | 3.220 | 1725 |

### 5c Viscosity

The development of Rayleigh-Taylor instabilities on the surface of liquid metal due to the interaction of electric currents induced in the liquid layer with magnetic fields at the edge of a plasma has been observed at JET in disruption damage of inconel heat shields [30]. The viscosity of beryllium has been measured to be $10^{-3}$ poise at melting temperature and decreases with temperature as shown in Figure 4. The material grade is not known [20].

### 5d Vapour Pressure

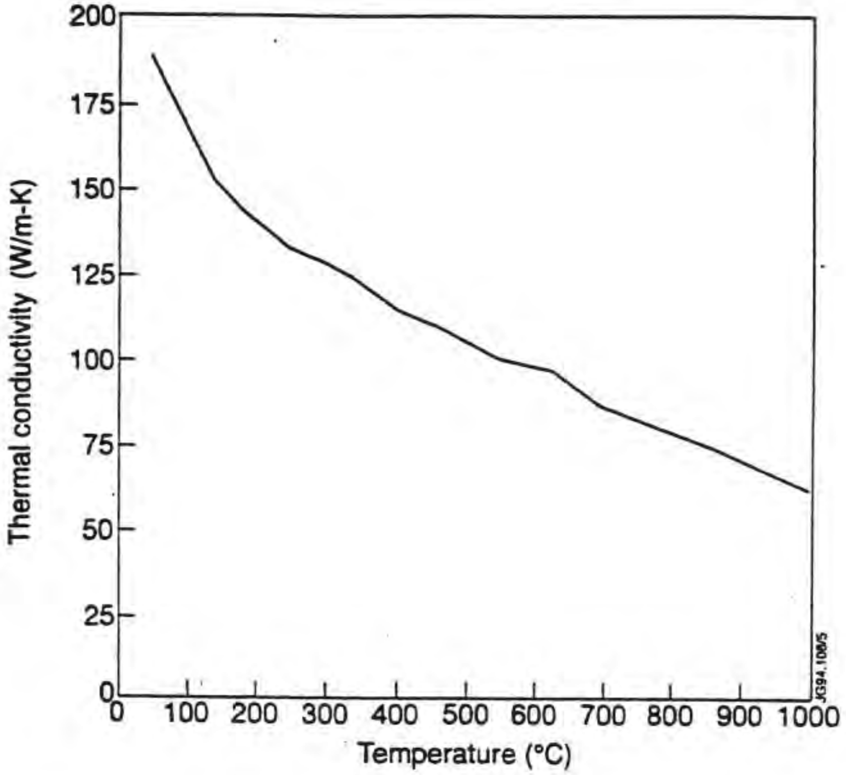
In a PFC application the amount of wall material released into the plasma is crucial to the purity of the edge plasma and ultimately to the performance of the core plasma. In addition to the physical process of evaporation, sputtering by hydrogenic species, by other impurities and by beryllium particles already released contribute towards the net wall influx of beryllium atoms into the plasma.

The vapour pressure of beryllium in solid form is given by [15]

$$\log p\ (\mathrm{Torr}) = 11.279 - 0.56 \log T - 17.058\ T^{-1} \quad 298 < T < 1560\ \mathrm{K}$$

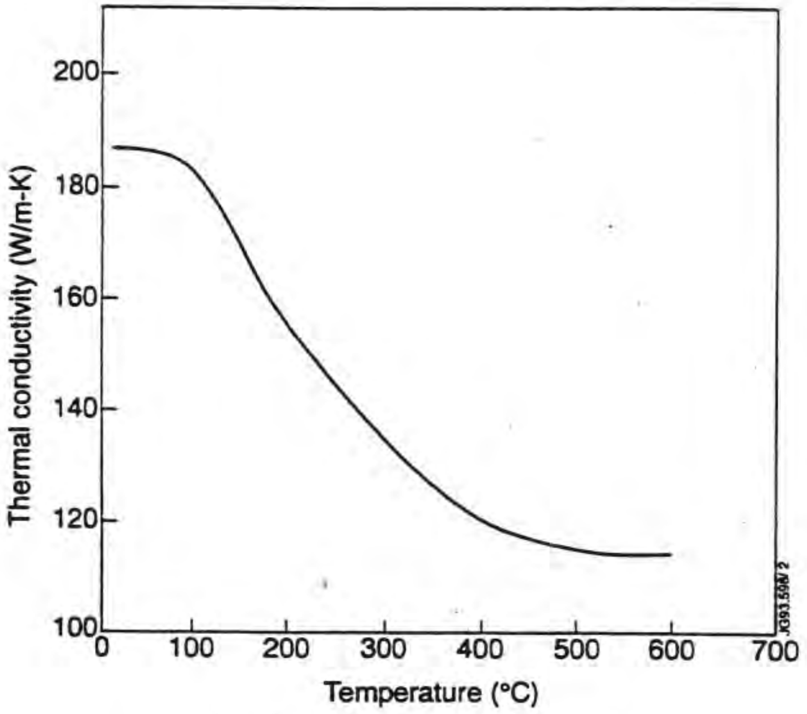
and for the liquid form by [15]

$$\log p\ (\mathrm{Torr}) = 12.483 - 1.04 \log T - 16.518\ T^{-1} \quad 1560 < T < 2745\ \mathrm{K}.$$



S65B VHP Beryllium

Fig. 4 Thermal conductivity of S-65B grade VHP Be [21].



IM sheet with BeO circa 100ppm

Fig. 5 Thermal conductivity for IM sheet [29].

For commercially available beryllium material, experience at JET suggests that the method of fabrication i.e. casting versus powder metallurgical methods, does play a role in determining the total evaporation rate of beryllium from a surface. As BeO melts at substantially higher temperatures than Be, the preferential release of Be from a surface will tend to enrich the concentration of BeO and thus reduce the net total evaporation rate. Clearly the ionic and energetic bombardment of beryllium PFC in a tokamak will alter the geometric morphology of the surface. No systematic measurements of beryllium evaporation rates from samples modified this way have been reported.

## 6. UNIRRADIATED PROPERTIES

In this section the behaviour of thermomechanical properties versus temperature will be reviewed with emphasis on measurements made according to published standards. For example ASTM volume 3.01 [31] lists accepted procedures for metals testing. VHP beryllium block has been the form for which the most extensive investigation of properties has been made since the review by Pinto [14]. New HIP grades have been shown to exhibit nearly isotropic properties. Thermomechanical data for these grades have yet to be fully measured at elevated temperatures.

### 6a Thermal Conductivity

The majority of thermal conductivity data for beryllium was generated during the years 1940-1955. Although most of this data was obtained from tests conducted on single crystals at cryogenic temperatures, or on material in a strong magnetic field, there is some data which may pertain to the properties of beryllium made by the current PM process. The most complete review of the older data is to be found in Thermophysical Properties of Matter Vol. 1 [32]. Room temperature values quoted therein of thermal conductivity for material which has characteristics of commercial beryllium range from 135 to 200 W/m-K, with a recommended value of 180 W/m-K.

As shown in Table 5, beryllium of modern purity has a room temperature thermal conductivity in the range 204-219 W/m-K [17]. This is 15-20% higher than the widely accepted values for beryllium [32]. Note that the method of measurement for the longitudinal bars [17] follows ASTM standard C-1045-80. Since the most widely used commercial grade in the table is S-200F, the value 204 W/m-K is recommended as the thermal conductivity at room temperature.

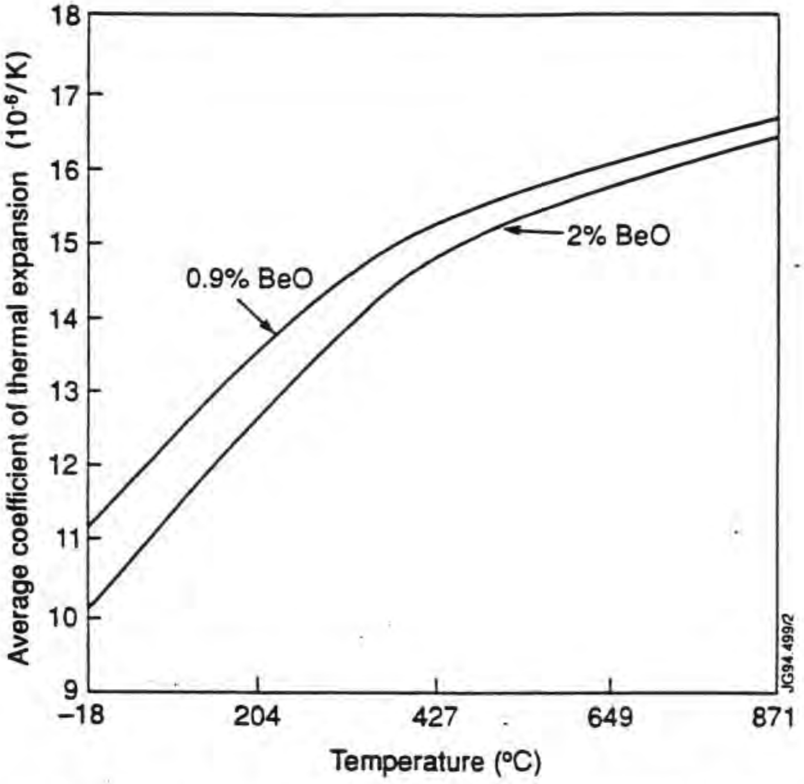


Fig. 6 Coefficients of thermal expansion [36].

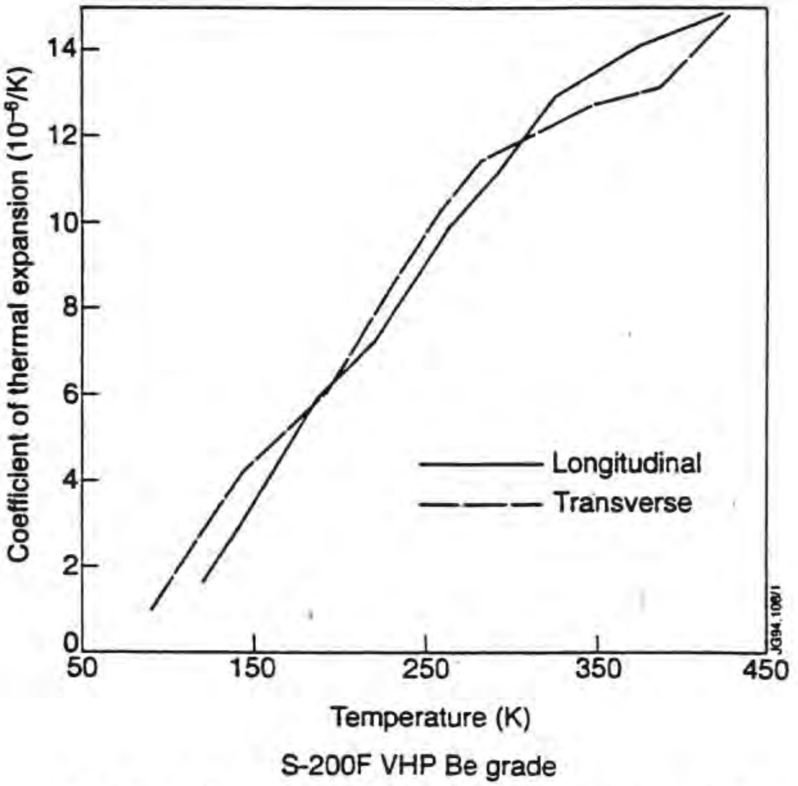


Fig. 7 Coefficient of thermal expansion [34].

Table 5 Thermal Conductivity of Be at 25°C

| Grade | wt% BeO | Form | Process | Measurement Method | k (W/m-K) |
|---|---|---|---|---|---|
| Spherical Powder | ~0.5 | Block | HIP | Longitudinal Bar | 204 |
| Spherical Powder | ~0.5 | Block | VHP | Longitudinal Bar | 216 |
| BG-170 | ~2 | Block | CIP/Sinter/ Coin | Longitudinal Bar | 215 |
| S-200F | < 1.50 | Block | VHP | Longitudinal Bar | 204 |
| SR-200 | < 2.0 | Block | VHP/Roll | Laser Flash | 219 |

Figures 4 and 5 show measured values of thermal conductivity as a function of temperature. Thermal conductivity of VHP grade S-65B with 0.9wt% of BeO is shown as a function of temperature in Figure 5 and also in Table 4 above. Figure 5 shows data for IM beryllium sheet for which the samples are likely to contain less than 100 ppm of BeO [29]. The measured value of 187 W/m/K at 20°C for ingot sheet is lower than the reference value of Table 1.

### 6b Coefficient of Thermal Expansion

For evaluation of older CTE data, the anisotropy of various Be products must be taken into account, as well as the %BeO content. The introduction of HIP Be products has provided grades that exhibit a more isotropic CTE response. However, these HIP products have not been characterised over the full temperature range of interest for fusion.

Figure 6 shows average values of CTE versus temperature for two different BeO contents: 0.9 wt% BeO and 2.0 wt% BeO [14]. As seen in Figure 6 CTE for the higher content to vary between $10 \times 10^{-6}$/K and $16.4 \times 10^{-6}$/K for a temperature span of -18 to 871°C. The CTE of beryllium with 0.9% BeO is seen to vary between $11 \times 10^{-6}$/K and $16.7 \times 10^{-6}$/K for the same temperature range. This indicates that higher BeO content decreases CTE. This trend is confirmed by comparing the CTE values for several high

BeO content, and Be/BeO composite materials. As the volume % BeO is increased from 20 to 60, the CTE for the 0 to 25°C temperature range drops by about 33% [33].

Figure 7 shows CTE values for VHP grade S-200F (1.06 wt%BeO) from 89 to 430 K [34]. In the longitudinal direction, CTE varies between $1.6 \times 10^{-6}$ /K and $14.7 \times 10^{-6}$/K as the temperature ranges between 120 and 425 K. In the transverse direction, CTE varies between $0.9 \times 10^{-6}$/K and $14.7 \times 10^{-6}$/K as the temperature ranges between 89 and 430 K. Note that the difference in CTE between the two orientations decreases with temperature, and is negligible at 430 K.

CTE values over the temperature span 6 to 64°C for the S-65B grade of VHP beryllium are reported to be $11.66 \times 10^{-6}$/K in the transverse direction and $11.54 \times 10^{-6}$/K in the longitudinal direction [35]. This grade of VHP beryllium typically contains 0.9 wt% BeO, and has a lower CTE than the S-200F grade, as expected.

Figure 8 shows average CTE values for beryllium sheet made using IM [29]. There is little effect of orientation within the plane of the sheet. Although the BeO content was not reported, it was expected to be less than 100 ppm. Values for CTE range from $7.2 \times 10^{-6}$/K at – 188°C to $17.2 \times 10^{-6}$/K at 707°C; CTE at 20°C is $11.3 \times 10^{-6}$/K.

### 6c Electrical Resistivity

Resistivity is strongly affected by contaminant concentration and by heat treatments which determine whether the contaminants are in solution or are precipitates. Resistivity is lower when impurities have been precipitated out of solid solution for both PM and IM beryllium. High purity is always associated with lower electrical resistivity.

Figure 9 shows a plot of electrical resistivity as a function of temperature for VHP Be with 1.7 wt% BeO [16]. Values range from $4.47 \times 10^{-8}$ Ohm-m at 23°C to $45.65 \times 10^{-8}$ Ohm-m at 1000°C. There is little difference (2%) in electrical resistivity at 21°C between the longitudinal and transverse orientations in the VHP billet.

The electrical resistivity of beryllium ingot sheet is shown in Figure 10 for temperatures between 20°C to 527°C [29].

### 6d Youngs Modulus

The most extensively documented and detailed measurements of Youngs modulus have been presented by Haws for a VHP billet of S-200F material [19]. For a sample with 1.06% by weight of BeO measured values are reported of 311 GPa ± 6.9 GPa and

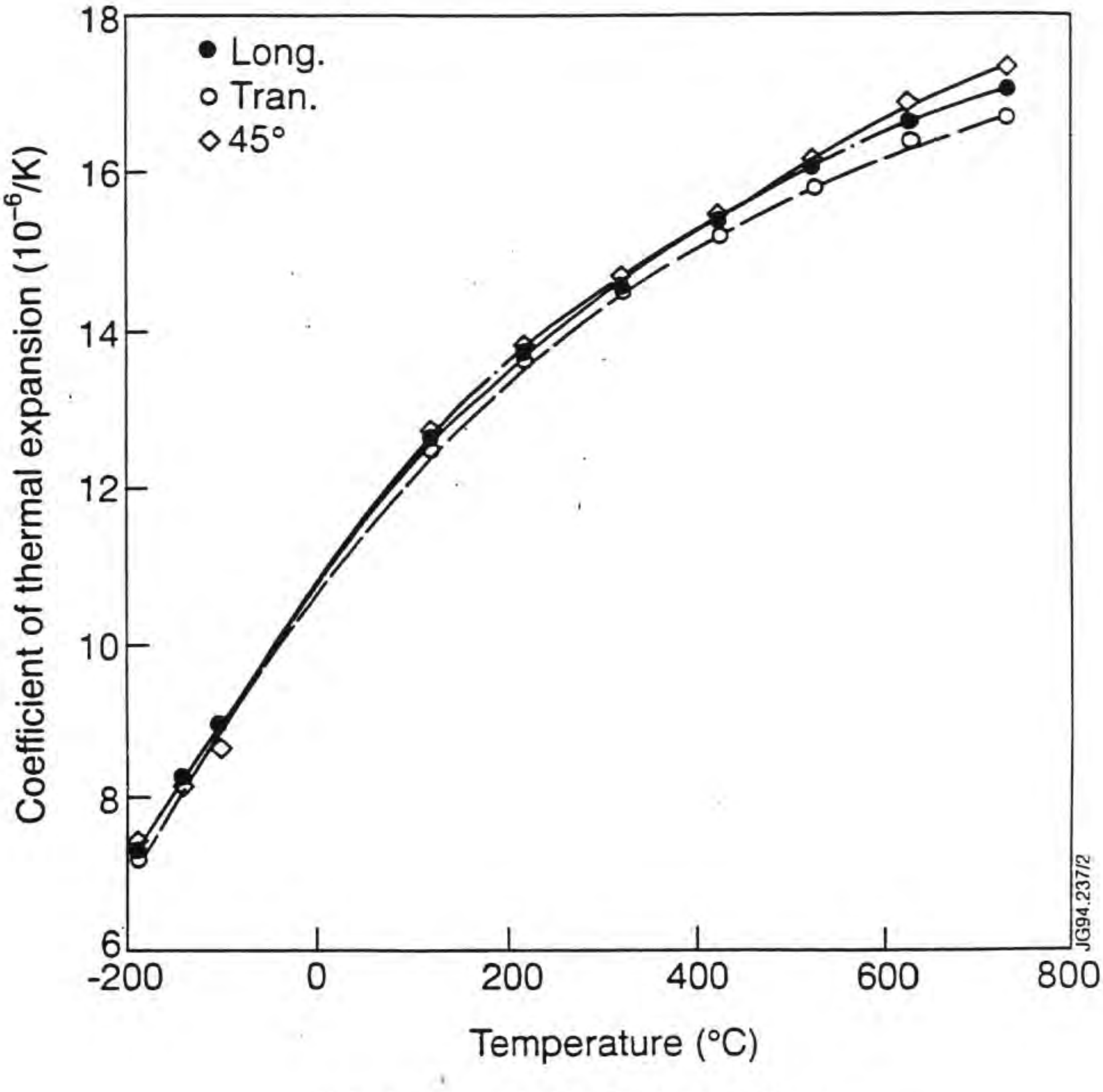
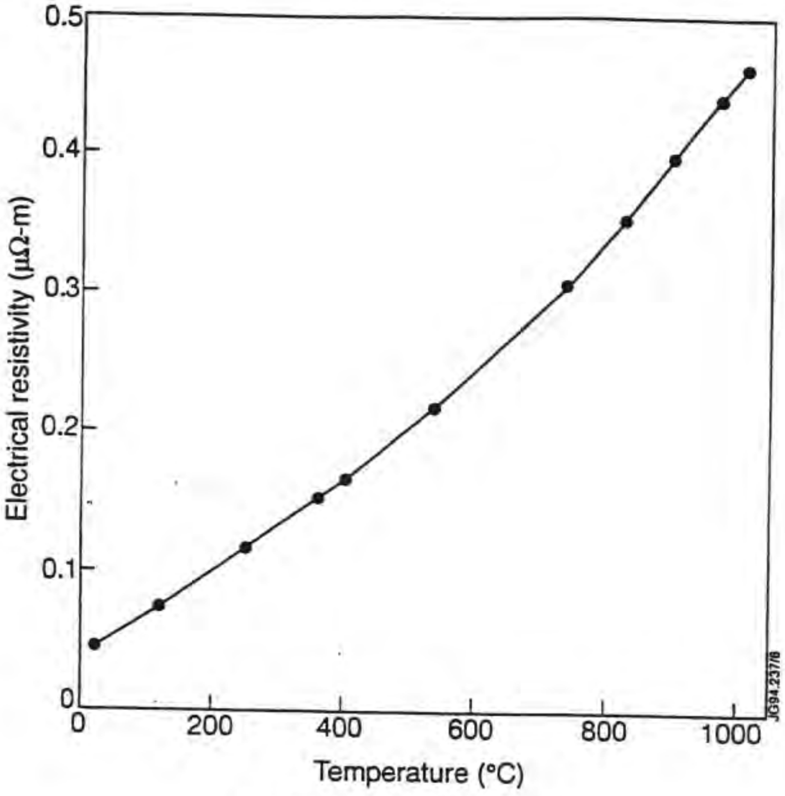
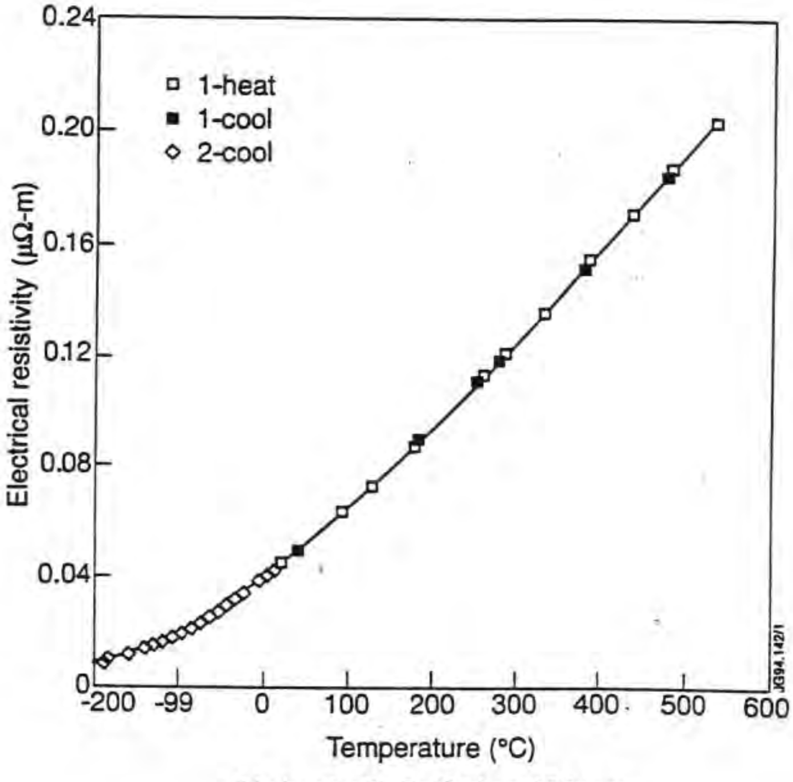


Fig. 8 Coefficient of thermal expansion [29].



Be VHP with 1.7 wt% BeO

Fig. 9 Electrical resistivity VHP Be [16].



IM sheet with BeO circa 100ppm

Fig. 10 Electrical resistivity of IM Be sheet [29].

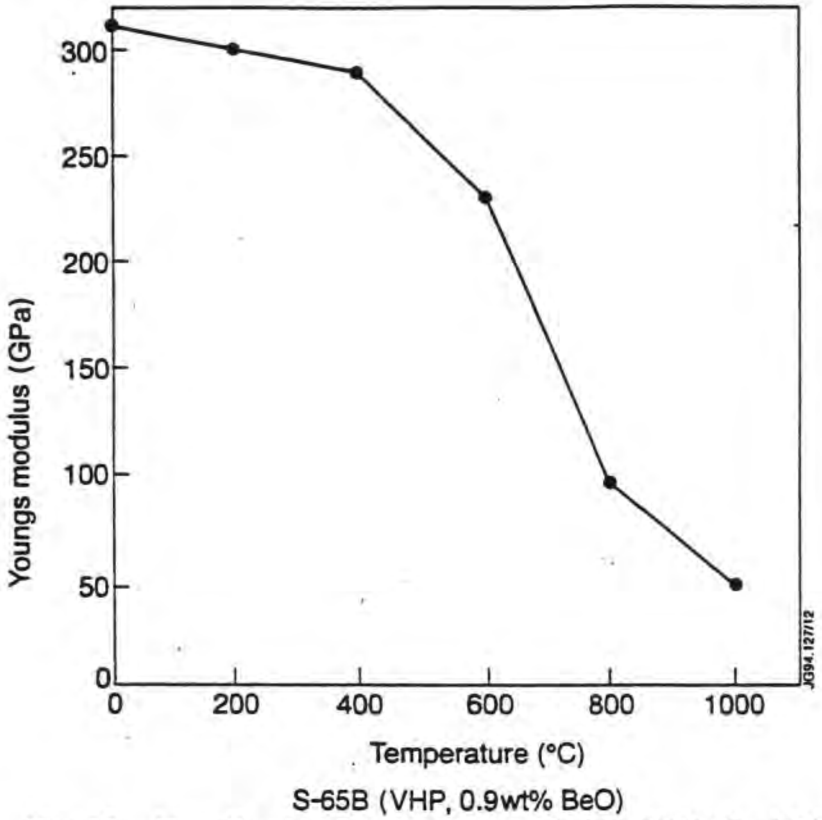


Fig. 11 Tensile elastic modulus of S-65B VHP Be [21].

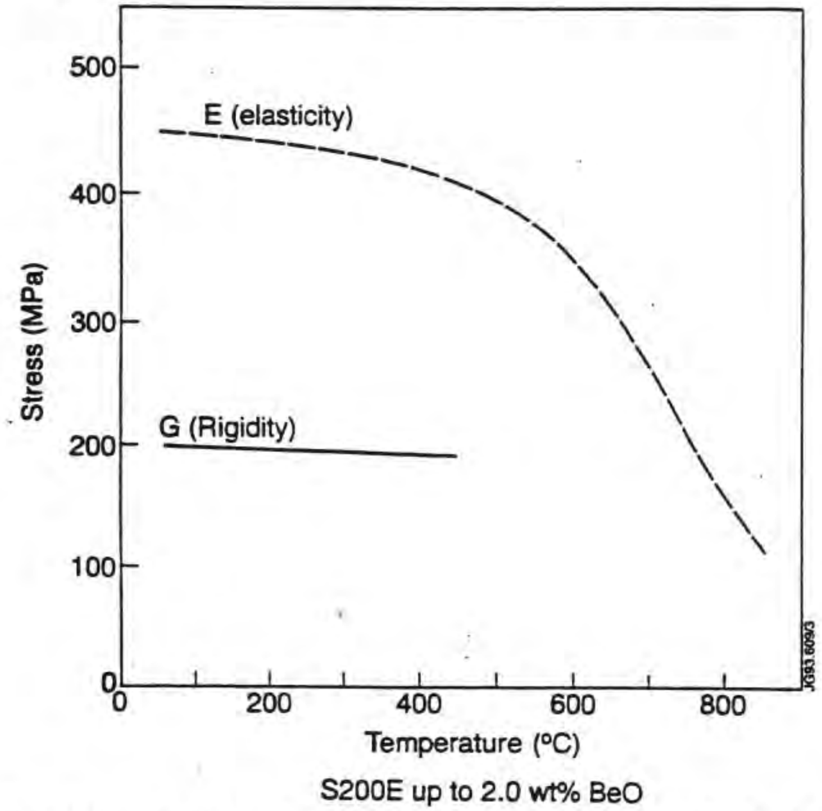


Fig. 12 Elastic and shear moduli for S-200E VHP Be [36].

with 1.06% by weight of BeO measured values are reported of 311 GPa ± 6.9 GPa and 310 GPa ± 4.8 GPa for the tensile modulus in the longitudinal and transverse directions [19]. Variation with temperature of the tensile elastic modulus is shown for S-65B (VHP, 0.9wt% BeO) in Figure 11 and also in Table 6 below.

Table 6: Tensile Elastic Modulus S-65B [21].

| Modulus GPa | 310 | 300 | 290 | 230 | 97 | 48 |
|---|---|---|---|---|---|---|
| Temperature °C | 0 | 200 | 400 | 600 | 800 | 1000 |

### 6e Shear modulus

Shear modulus of S-200F grade VHP beryllium was measured at room temperature by torsion according to the ASTM E-143 procedure. The average shear modulus was determined to be 135 MPa ± 4.8 MPa and 134 MPa ± 4.8 MPa for the longitudinal and transverse directions respectively [19]. Shear rupture modulus was determined from the maximum stress of the stress-strain curve to be 297 MPa ± 13 MPa in the longitudinal direction and 309 MPa ± 8.3 MPa in the transverse direction [19].

Figure 12 shows the variation of shear modulus with temperature for S-200E grade beryllium [36]. This grade is no longer produced.

### 6f Poisson's Ratio

Table 7: Room Temperature Poisson's ratio for S-200F VHP Be with 1.06 wt% BeO.

| **Orientation** | **Stress Axis** | **Direction of Orthogonal Strain** | **Poisson's Ratio** |
|---|---|---|---|
| LC | Longitudinal | Circumferential | 0.102 |
| | | | 0.064 |
| | | | 0.072 |
| LR | Longitudinal | Radial | 0.102 |
| | | | 0.080 |
| | | | 0.105 |
| TL | Transverse | Longitudinal | 0.069 |
| | | | 0.071 |
| | | | 0.108 |
| TR | Transverse | Radial | 0.102 |
| | | | 0.058 |
| | | | 0.066 |

Table 7 above shows the only known published data on accurately measured room temperature Poisson's ratio for a modern grade of beryllium [37].

Poisson's ratio was determined at room temperature according to ASTM standard E-

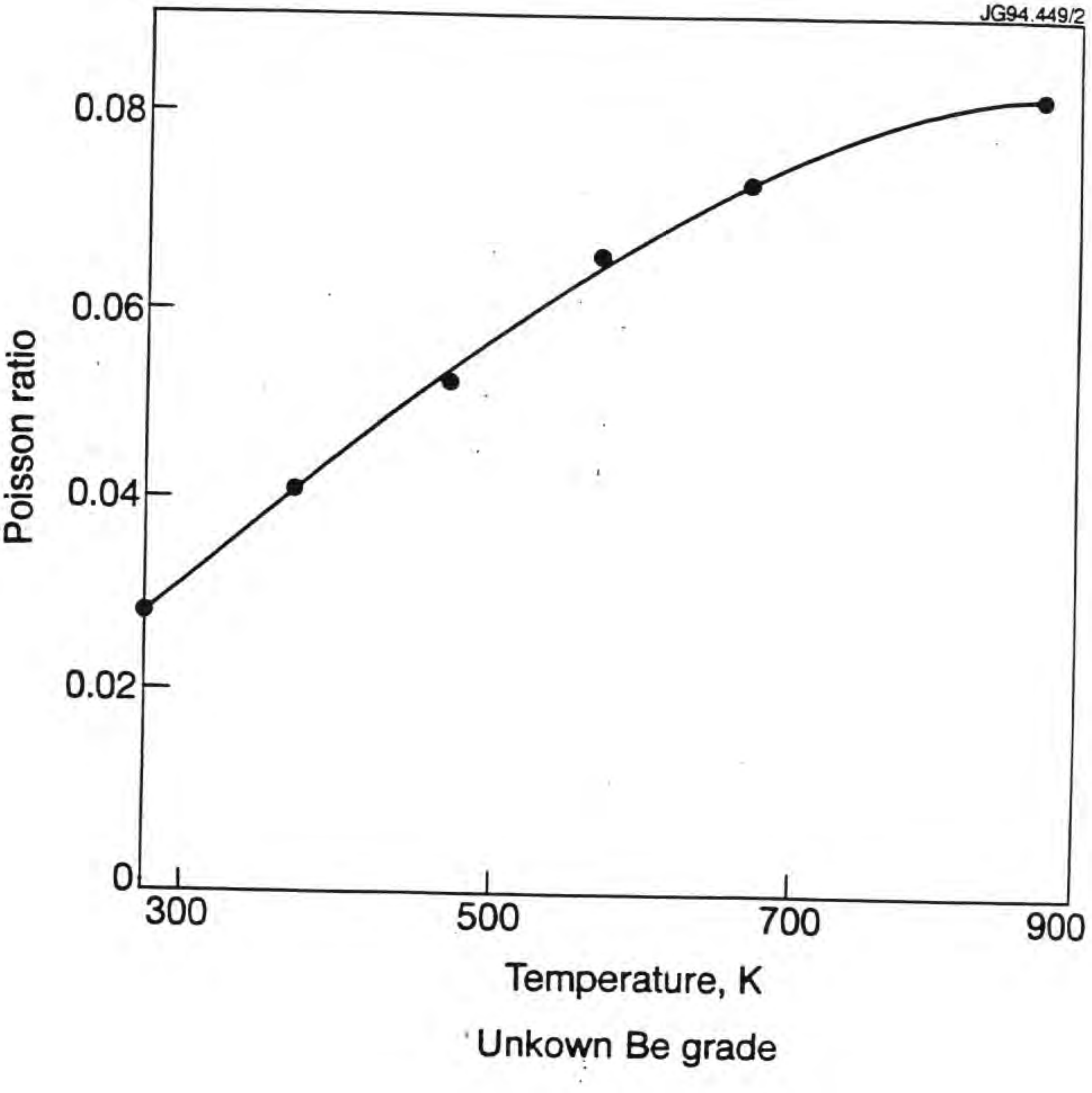


Fig. 13 Poisson's ratio for an unknown grade of Be [38].

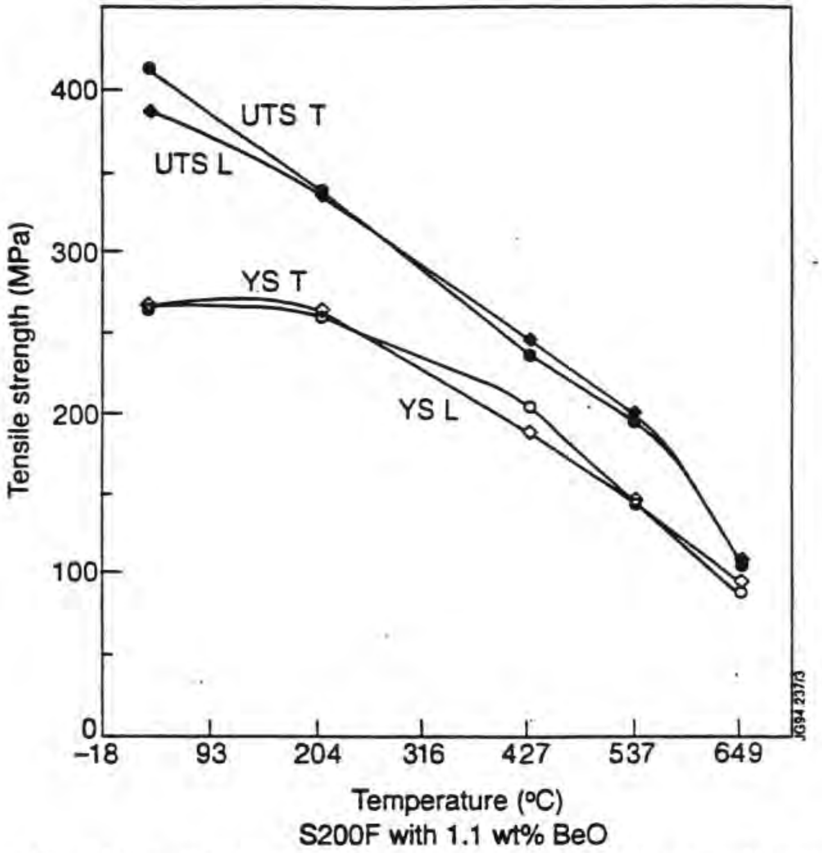


Fig. 14 Ultimate tensile strength and 0.2% offset yield strength for S-200F grade VHP Be [19].

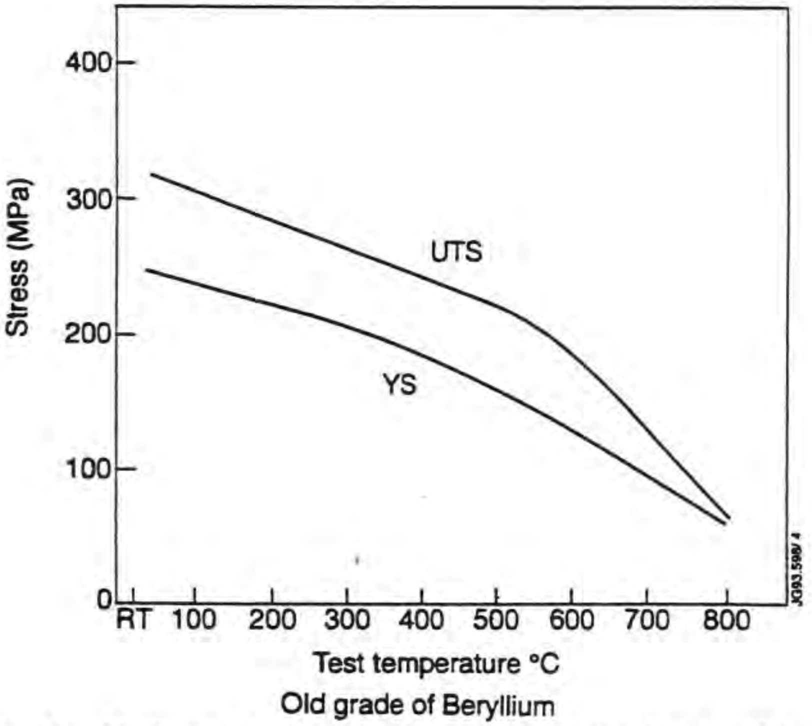


Fig. 15 Ultimate tensile strength and 0.2% offset yield strength for earlier production grade of VHP Be [14].

132-61. The tests were performed using sheet geometry specimens that were machined from a piece of as-pressed beryllium; the sheet geometry was not produced by rolling. Specimens were tested in four orientations: LC, LR, TL, and TR. The first letter specifies the orientation of the stress axis of the specimen to the vacuum hot pressing direction: L or T. Longitudinal (L) signifies that the stress axis was parallel to the pressing direction, and transverse (T) signifies that the stress axis was perpendicular to the pressing direction. The second letter (R, C or L) compares the orientation of the orthogonal strain to the pressing direction. The strain was either in a radial (R) direction in the cylindrical billet compared to the pressing direction, circumferential (C), or longitudinal. There is significant scatter in the data. This is a low value that may be difficult to measure precisely.

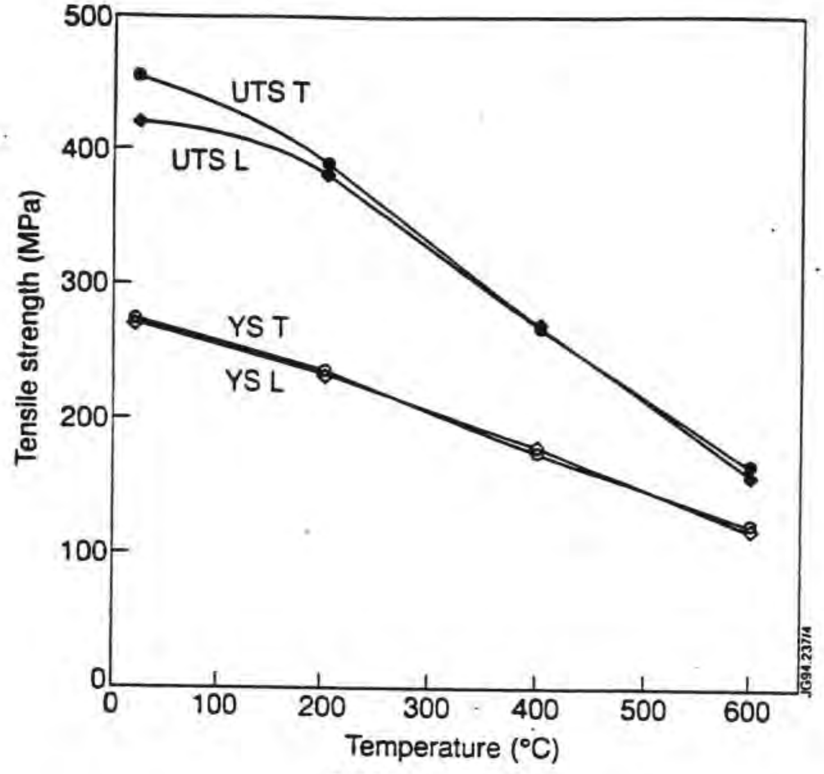
No measurements of Poisson's ratio as a function of temperature have been reported for modern commercial PM grades of beryllium. However, by analogy for data presented for older forms of beryllium it is expected that the value of Poisson's ratio will increase with increasing temperature [13]. Figure 13 shows data for an unknown grade of beryllium [38]. However, the room temperature values therein are lower than measured e.g. Table 7 above. This data may have been derived from measurements of shear modulus. A different report on the variation of Poisson's ratio with temperature [39] appears to show a falling tendency with increasing temperature.

## 6g Ultimate Tensile Strength

### *6g.1 VHP Block*

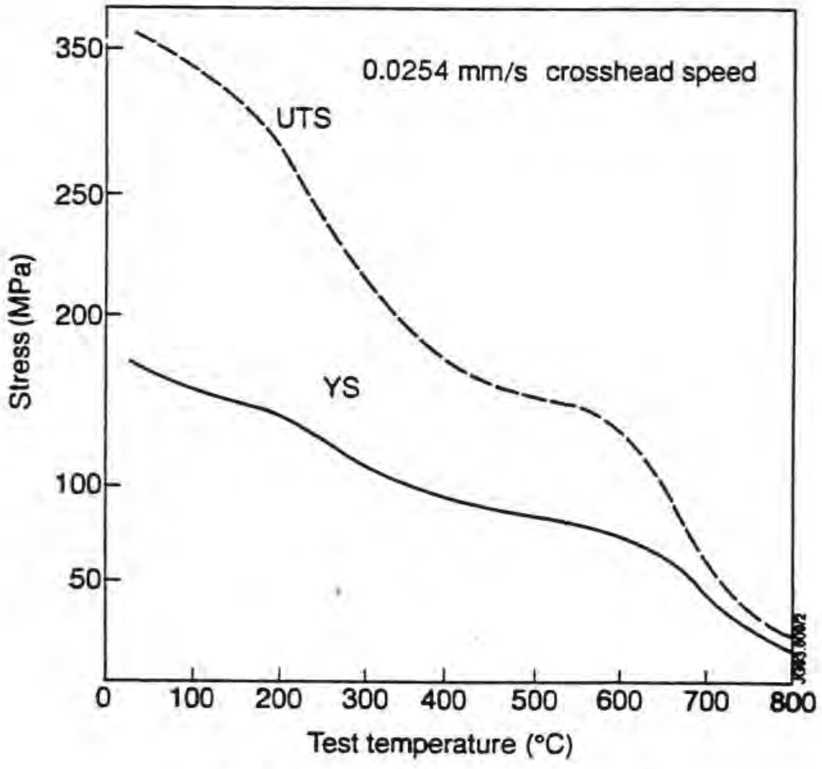
Figure 14 shows ultimate tensile strength (UTS) versus temperature for S-200F grade Be (1.5% BeO, 98.5% Be, impact ground, VHP). Values range from 382 and 408 MPa at room temperature for longitudinal and transverse directions respectively to 108 and 107 MPa for longitudinal and transverse directions at 649°C [19]. Note that the data points are mean values from triplicate tests on the same lot of material. Testing was done in accordance with ASTM specifications E8, E4 and E21, with additional requirements specified by the Materials Advisory Board.

Figure 15 shows data to 800°C for grade that is no longer produced [14]. This particular grade had lower strength than S-200F, but the plot is useful because it indicates the



S-65B VHP material

Fig. 16 Ultimate tensile strength and 0.2% offset yield strength for S-65 V.HP Be [21].



IM sheet with BeO circa 100ppm

Fig. 17 Ultimate tensile strength and 0.2% offset yield strength for IM Be sheet [24].

general trend of UTS at higher temperatures. Note that at 800°C UTS is only 18% of the UTS at room temperature.

Figure 16 shows ultimate tensile strength (UTS) versus temperature for S-65B grade Be (1.0% BeO, 99.0% Be, impact ground, VHP) [21]. Values range from 421 MPa and 454 MPa at room temperature for longitudinal and transverse directions respectively, to 160 MPa and 168 MPa at 600°C for the same directions. This grade of beryllium has an 11% greater UTS at room temperature than S-200F.

### *6g.2 HIP Block*

S-200F-H is a grade (HIP, 1.5wt% BeO, impact ground) formed by HIP instead of VHP. Table 8 shows data for room temperature mechanical properties [40]. As expected for a HIP product, there is no statistically significant difference in mechanical properties between two orthogonal directions. This HIP grade has about 8 MPa greater UTS than the equivalent VHP grade transverse direction. The transverse direction is the stronger of the two directions in VHP material.

Table 8: Room Temperature Mechanical Properties of S-200F-H Block [40]

| **Orientation** | | **No. of Samples** | **UTS (MPa)** | **0.2% YS (MPa)** | **Elongation (%)** |
|---|---|---|---|---|---|
| Longitudinal | mean | 67 | 438 | 343 | 4.6 |
| | std.dev. | | 9.682 | 16.74 | 0.5601 |
| Transverse | mean | 66 | 447 | 346 | 5.3 |
| | std.dev. | | 10.75 | 16.65 | 0.6105 |

UTS was measured for S-65B purity material made by cold pressing, then sintering and finally hot isostatic pressing (CP/Sinter/HIP) instead of vacuum hot pressing (VHP) [41]. The value at 370°C is 228 MPa and the value at 605°C is 123 MPa. S-65B has BeO content at or below 1.0 wt%.

### *6g.3 Ingot Sheet and Powder Metallurgy Sheet*

Bulk ingot beryllium will generally have lower strength than PM billet due to the differences in grain size, BeO size, and BeO distribution. Sheet is the most notable ingot product because it has lower oxygen content than sheet derived by PM, and also shows greater ductility above 200°C. Recent measurements of UTS as a function of temperature for ingot sheet are shown in Figure 17 [29]. Although the BeO content was not measured, it was expected to be less than 100 ppm. Figure 18 also shows UTS versus temperature for SR-200 (sheet of PM origin) [36].

## 6h Yield Strength

### *6h.1 VHP Block*

Figure 14 also shows the tensile yield strength (YS) versus temperature for S-200F grade Be (1.5% BeO, 98.5% Be, impact ground, VHP) [19]. Values range from 263 and 262 MPa at room temperature for longitudinal and transverse directions, respectively, to 90 and 95 MPa for longitudinal and transverse directions at 649°C. These data points are mean values from triplicate tests on the same lot of material.

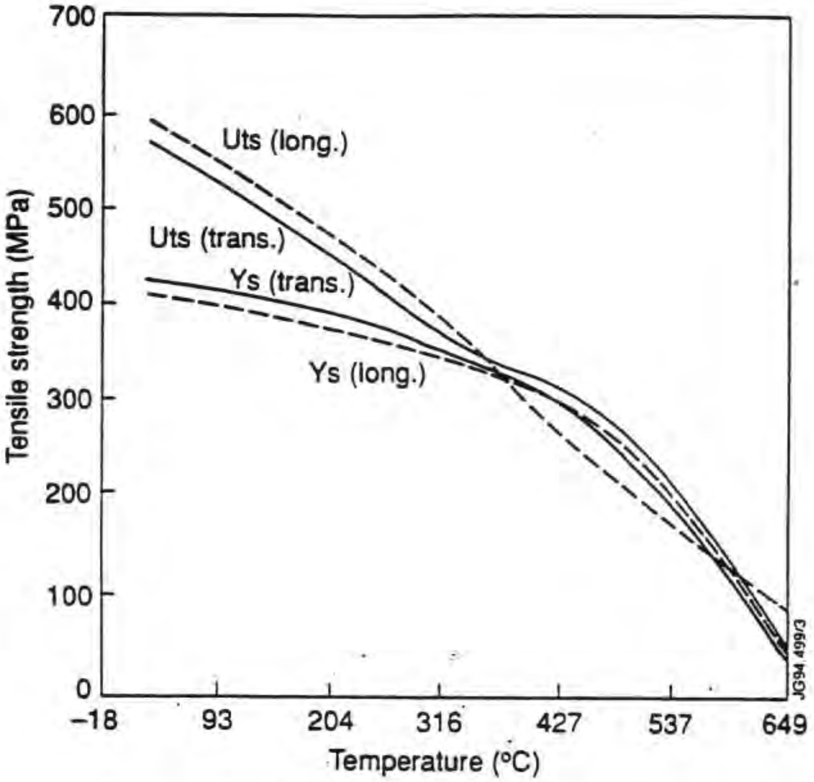
Figure 15 shows data for temperature to 800°C for a grade no longer in production [14] which had lower strength than S-200F. The plot is useful because it indicates the trend of yield strength at higher temperatures. Note that YS for this grade at 800°C is about 22% of the YS at room temperature.

Figure 16 shows a plot of 0.2% YS versus temperature for S-65B grade Be (1.0% BeO, 99.0% Be, impact ground, VHP) [21]. Values range from 270 and 273 MPa at room temperature for longitudinal and transverse directions, respectively, to 119 and 122 MPa for longitudinal and transverse directions at 600°C.

### *6h.2 HIP Block*

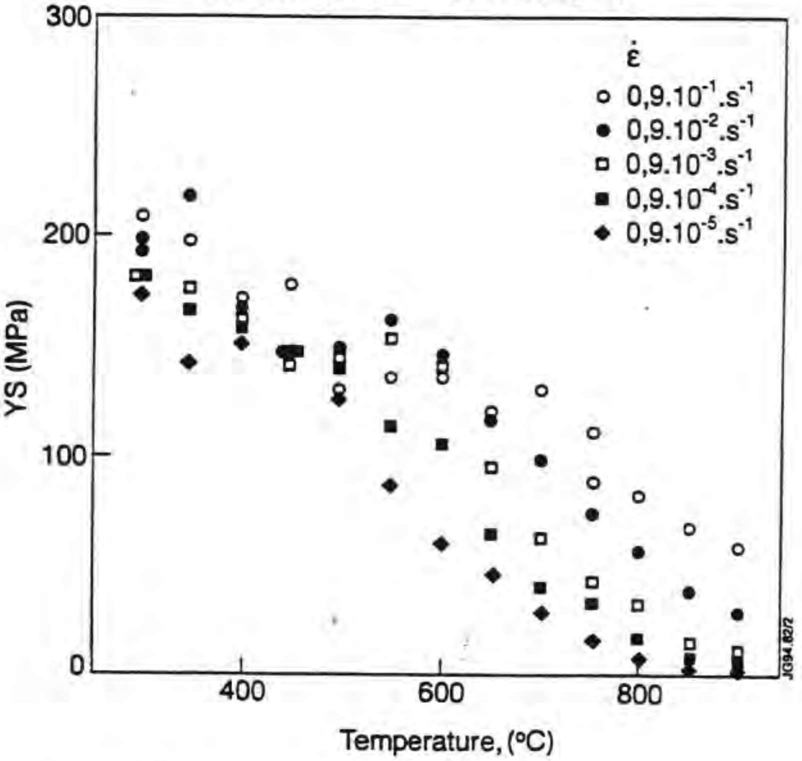
Table 8 above lists data for room temperature mechanical properties for a sample of S-200F-H. As expected for a HIP product, there is no statistically significant difference in mechanical properties between two orthogonal directions. This grade has a 0.2% YS that is 80 MPa greater than the YS for an equivalent VHP grade in the transverse direction. The transverse direction is the stronger of the two directions in VHP material.

The behaviour of YS versus temperature was measured for S-65 purity material made



SR–200 Cross-rolled sheet

Fig. 18 Ultimate tensile strength and 0.2% offset yield strength for SR-200E PM Be sheet [36].



S65 Be VHP 0.6 wt % BeO

Fig. 19 0.2% offset yield strength as a function of temperature and strain rate for S-65 VHP Be [42].

by the (CP/Sinter/HIP) method instead of (VHP) [41]. The value at 370°C is 133 MPa and the value at 650°C is 80.7 MPa.

The effects of strain rate upon yield strength may be important particularly as the research aspects of the ITER programme require PFCs to sustain variable loadings in normal operating regimes and extreme loadings under upset (disruption) events. Usually YS values are quoted for strain rates, in particular tensile strain rates of $10^{-6}$/sec. We have found only limited data for the effects of strain rate, cf. Figure 19 for a sample of S-65 (VHP, 0.6wt% BeO) [42]. Clearly the most extreme influence of strain rate on YS occurs at elevated temperatures i.e. nearly fivefold increase at 800°C for a strain rate change of five orders of magnitude.

### *6h.3 Ingot and Powder Metallurgy Sheet*

Recent measurements of yield strength [29] as a function of temperature for ingot sheet are shown in Figure 17. Although the BeO content was not measured, it is expected to be less than 100 ppm. Yield strength versus temperature for cross-rolled sheet of PM origin [36] is shown in Figure 18.

## 6i Uniform Elongation

Uniform elongation is the elongation at maximum load and immediately preceding necking in a tensile test. There is so little necking at room temperature that the tabulated data for room temperature percent elongation can be taken as uniform elongation. However, the reduction in area data discussed below shows that this approximation is not valid at higher temperatures.

## 6k Total Elongation

Total elongation is the total amount of permanent extension of a test piece broken in a tensile test.

### *6k.1 VHP Block*

Figure 20 shows a plot of total elongation versus temperature for S-200F grade Be (1.5% BeO, 98.5% Be, impact ground, VHP) [19]. Total elongation is expressed as

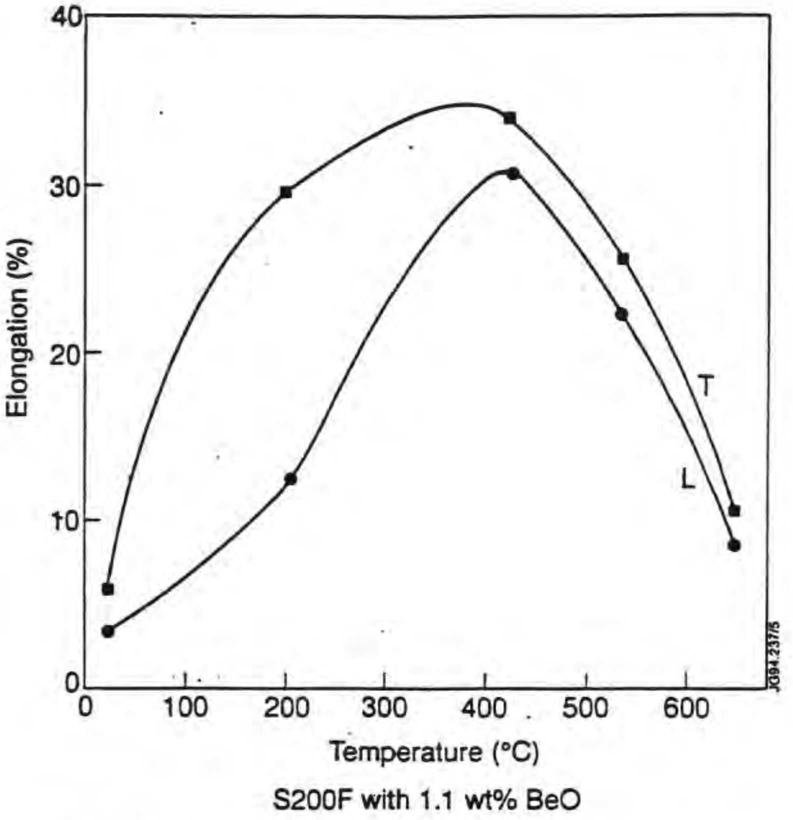


Fig. 20 Percent elongation for S-200F VHP Be [19].

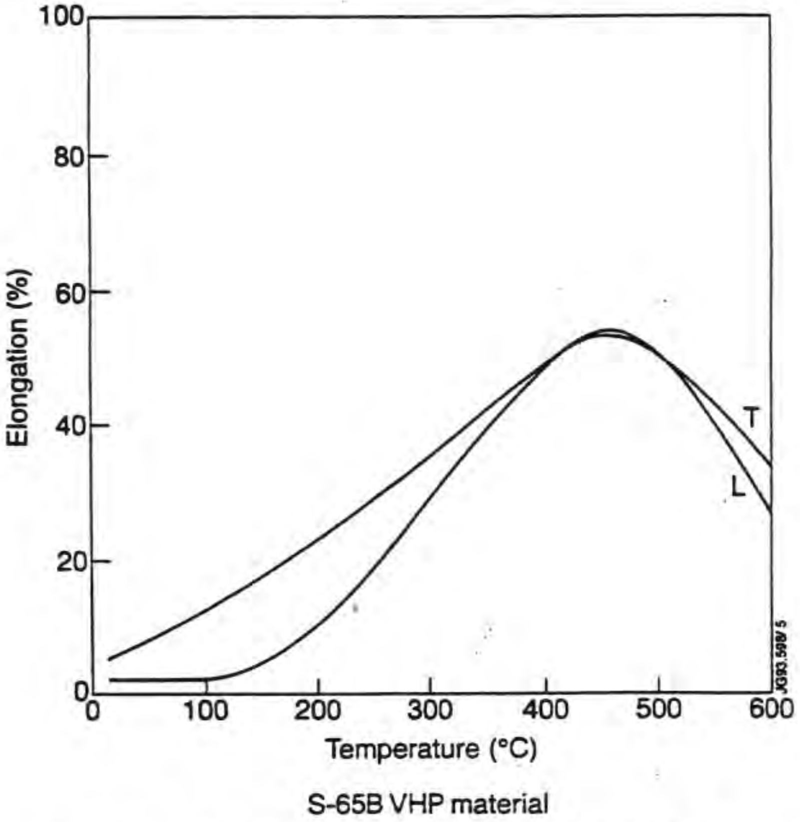


Fig. 21 Percent elongation for VHP S-65 Be [21].

percent elongation. Values range from 3.4 and 6.1 percent elongation at room temperature for longitudinal and transverse directions respectively to 30.4 and 33.8 percent elongation for longitudinal and transverse directions at 427°C. Percent elongation decreases as temperature increases from 427°C to 649°C. Note that the data points are mean values from triplicate tests on the same lot of material.

Figure 21 and Table 9 show the behaviour of percent elongation versus temperature for vacuum hot pressed S-65B grade Be (0.9% BeO, 99.0% Be, IG, VHP) [21]. Values range from 3.0 and 5.4 percent elongation room temperature for longitudinal and transverse directions respectively to 50.0 and 49.5 percent elongation for longitudinal and transverse directions at 400°C. Percent elongation decreases as temperature increases from 400°C to 600°C. The value of elongation at 400°C is a significant improvement over the values for S-200F grade material.

Table 9: Percent elongation versus temperature for vacuum hot pressed S-65B Be (1.0% BeO. 99.0% Be, impact ground, VHP) [21].

| Temperature (°C) | Orientation | Elongation (%) |
|---|---|---|
| 20 | L | 3.0 |
| 20 | T | 5.4 |
| 200 | L | 10.2 |
| 200 | T | 23.4 |
| 400 | L | 50.0 |
| 400 | T | 49.5 |
| 600 | L | 25.2 |
| 600 | T | 31.9 |

### *6k.2 HIP Block*

Percent elongation was measured for S-65B purity material made by the (CP/Sintering/HIP) method instead of (VHP) method [41]. These results are the average of four tests: at 370°C the elongation is 49.4%; the value at 650°C is 38.5%.
Table 8 above lists data for room temperature mechanical properties for S-200F-H for which there is no statistically significant difference in percent elongation between two orthogonal directions. This HIP grade has 4.9% elongation when longitudinal and transverse direction values are averaged together.

### *6k.3 Ingot and Powder Metallurgy Sheet*

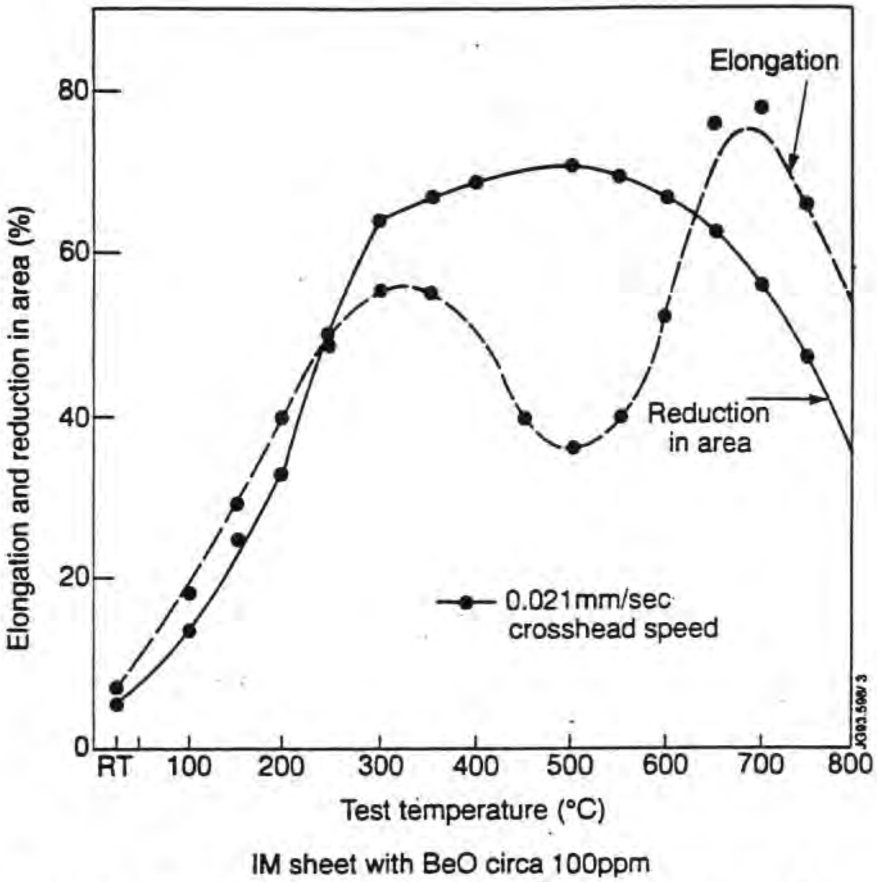


Fig. 22 Percent elongation and reduction in area for IM Be sheet [29].

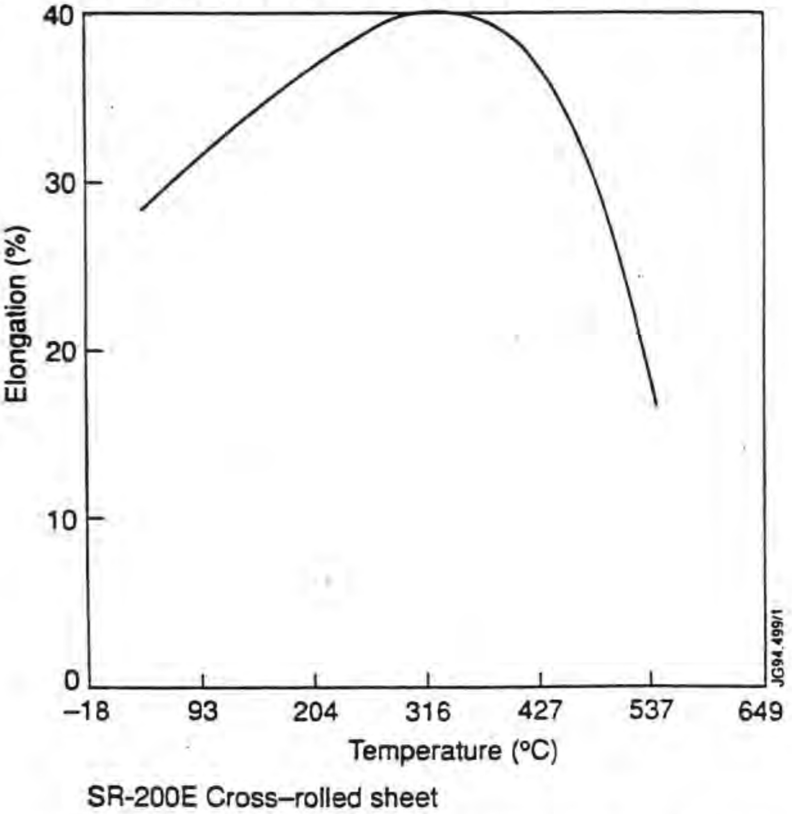


Fig. 23 Percent elongation for SR-200E PM Be sheet [36].

Figure 22 shows percent elongation as a function of temperature for ingot sheet and SR-200 powder metallurgy sheet [29]. Figure 23 shows percent elongation as a function of room temperature for SR-200 sheet (cross-rolled sheet of PM origin) [36]. Note that the in-plane elongation of IM sheet is lower than PM sheet up to 200°C, but that elongation for IM sheet is greater above that temperature. Out-of-plane elongation (or through-thickness elongation) is much lower than in-plane percent elongation for both types of sheet. For example, it is estimated that room temperature out-of-plane elongation for PM sheet is less than 1% [36]. Although there is no published data, IM sheet is thought to have greater out-of-plane elongation; it has performed better in elevated temperature bend formability tests [14].

## 61 Reduction of Area

### *61.1 VHP Block*

Figure 24 plots the reduction in area versus temperature for S-200F (1.5% BeO, 98.5% Be, impact ground, VHP) [19]. Values range from 3.3 and 5.9 percent reduction in area at room temperature for longitudinal and transverse directions respectively to 52.5 and 54.0 percent reduction in area for longitudinal and transverse directions at 427°C. Percent reduction in area decreases as temperature increases from 427°C to 649°C. Reduction in area values at the latter temperature are 7.3 and 9.7 percent, for the longitudinal and transverse directions respectively. Note that the data points are mean values from triplicate tests on the same lot of material.

### *61.2 HIP Block*

Measurements were made of percent reduction in area for S-65B purity material made by the (CP/Sinter/HIP) method instead of VHP [41]. These results are the average of four tests. These reported values are greater than corresponding data for S-200F VHP material. Reported values are 66.9% reduction in area at 370°C and 29.5% at 650°C.

### *61.3 Ingot and Powder Metallurgy Sheet*

Figure 22 shows the percent reduction in area as a function of temperature for ingot sheet (29).

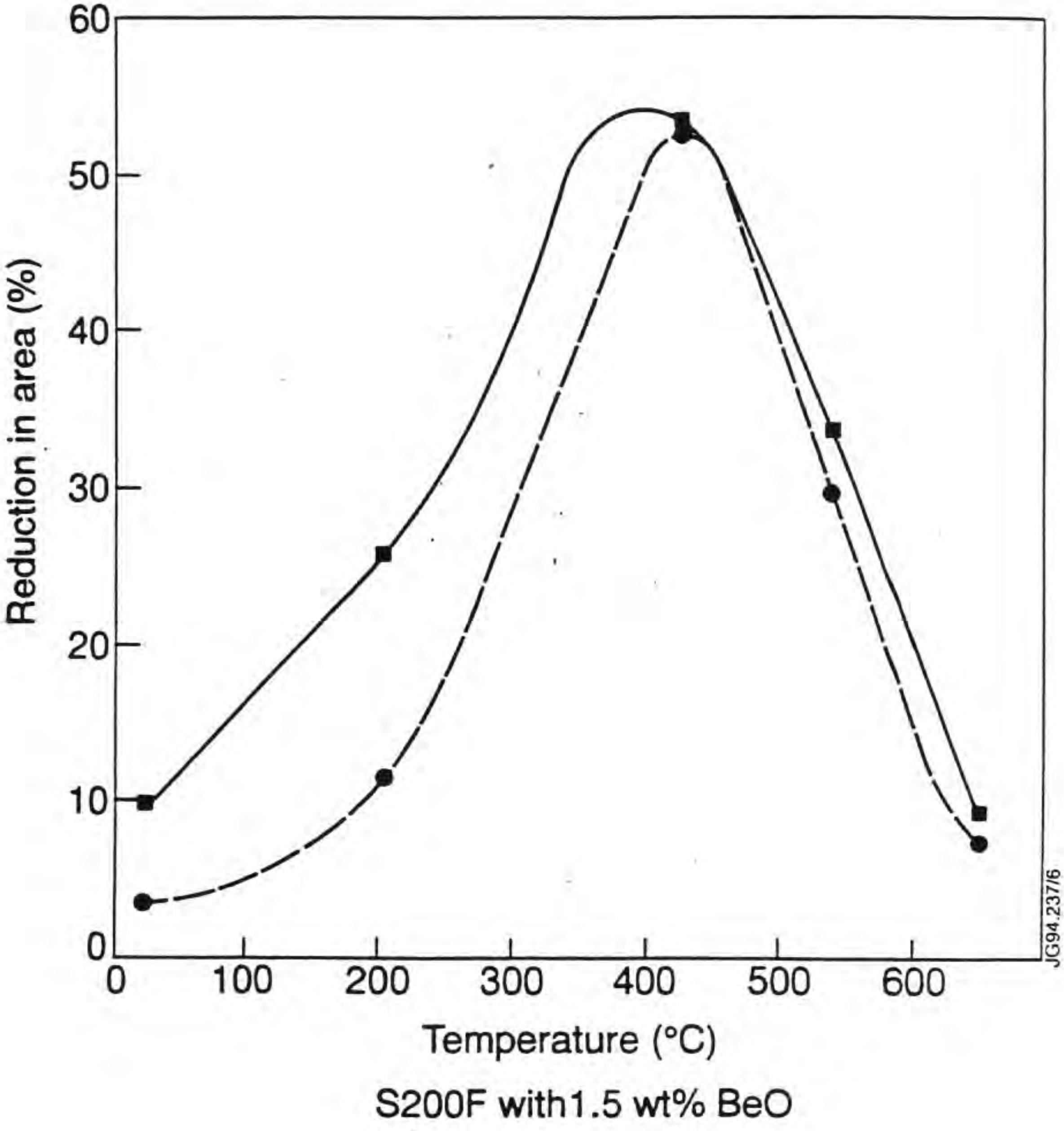


Fig. 24 Reduction in area for S-200F VHP Be [19].

## 6m Creep

There is no published data on creep of modern grades of beryllium.

Webster and Crooks [43] published a study for Be grades of unknown origin. HIP, VHP and cast Be samples of various purity were evaluated. Figure 25 shows the creep rate as a function of stress for a HIP Be sample (RR243), which had 1.56 wt% BeO, 550 ppm Fe, 200 ppm C, 16 ppm Al, 30 ppm Mg, and 36 ppm Si. Figure 26 compares the creep stress needed to give a creep rate of $10^{-1}$ percent per second for annealed RR243 and a specimen labelled as commercial purity hot pressed Be (sample 5310). Sample 5310 had 1.70 wt% BeO, 900 ppm Fe, 500 ppm C, 300 ppm Al, 200 ppm Mg, and 200 ppm Si. Creep stress to get the same rate of deformation was approximately the same for both grades to about 800°C. The higher purity HIP grade had significantly higher creep resistance above that temperature. Creep rate is inversely proportional to grain size [43], e.g. rates for 3000 µm and 4 µm grain sizes differ by several orders of magnitude.

Webster and Crooks [44] state that the creep strength of beryllium is significantly improved when the concentrations of low melting point impurities (Al, Si, Mg) found at the grain boundaries are decreased. They also reported that creep strength dropped markedly when the BeO content was substantially reduced below one percent.

Larson-Miller plots describe the empirical relationship of the engineering stress and time to rupture as a function of temperature. The following relationship is assumed:

$$(T + 460)(\log t_r + C) = m$$

where T is the temperature in °F, $t_r$ is the time to rupture, C is a constant that depends on the metal, and m is dependent on the initial engineering stress. Once C is determined, a master plot of engineering stress versus m allows one to predict rupture time for any combination of initial stress and temperature. Figures 27 and 28 show Larson Miller plots for S-200E grade VHP Be and SR-200E grade Be sheet [36]. Note that both materials are made from attrited powder whereas current Be grades are made from impact ground powder. The former have composition limits of 2.0 wt% BeO, 1800 ppm Fe, 1500 ppm C, and 1600 ppm Al.

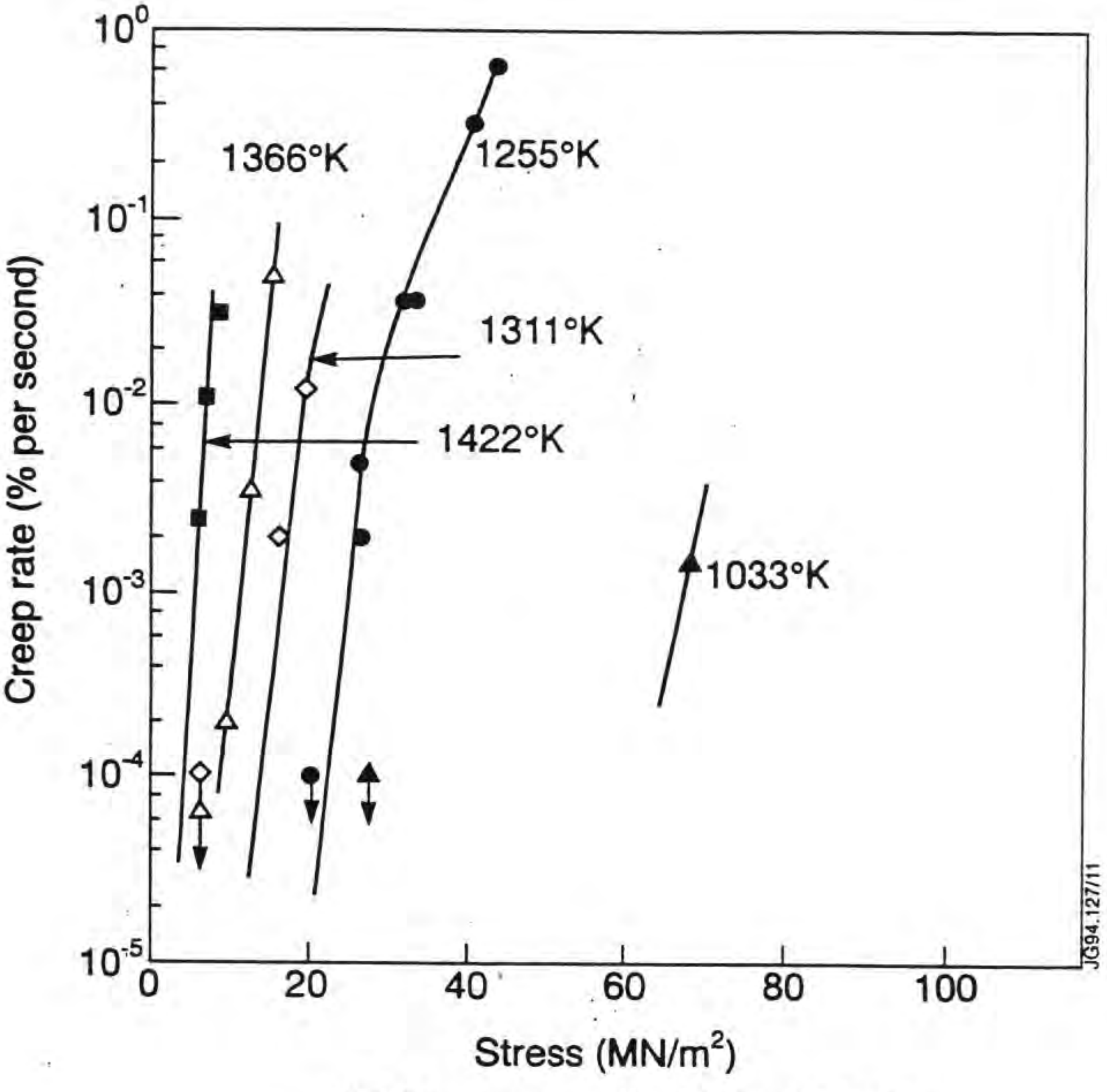


Fig. 25 Creep rate as a function of stress and temperature for sample RR243 (HIP, 1.56 wt% BeO, 550 ppm Fe, 200 ppm C, 16 ppm Al, 30 ppm Mg, and 36 ppm Si) [43].

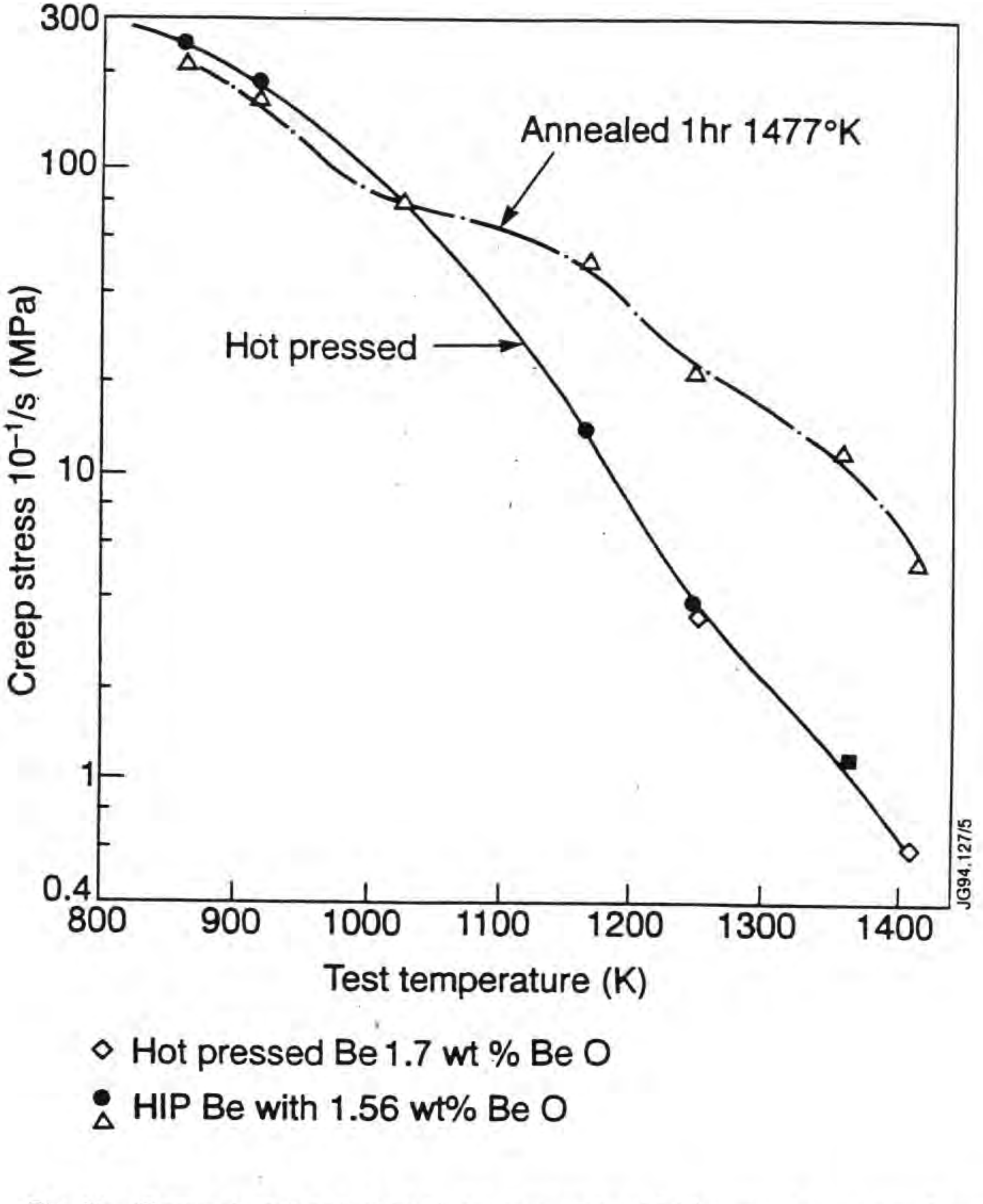


Fig. 26 Creep stress needed to give a creep rate of $10^{-1}$ percent per second as a function of temperature for annealed RR243 (HIP, 1.56 wt% BeO, 550 ppm Fe, 200ppm C, 16 ppm Al, 30 ppm Mg, and 36 ppm Si) and sample 5310 (VHP, 1.70 wt%BeO, 900 ppm Fe, 500 pmm C, 300 ppm Al, 200 ppm Mg, and 200 ppm Si) [43].

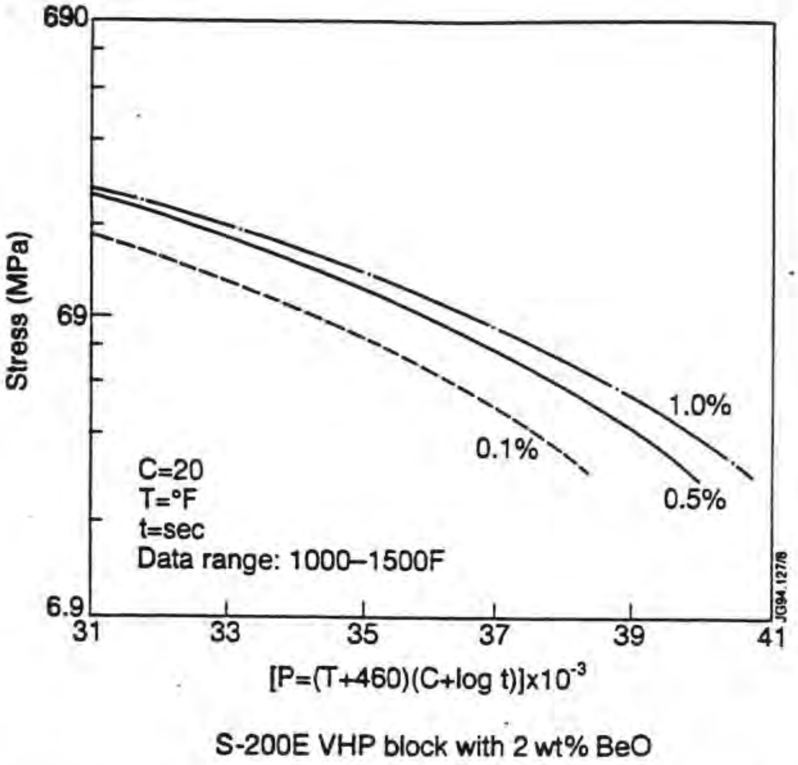


Fig. 27 Larson-Miller parameter versus stress for S-200E VHP block [36].

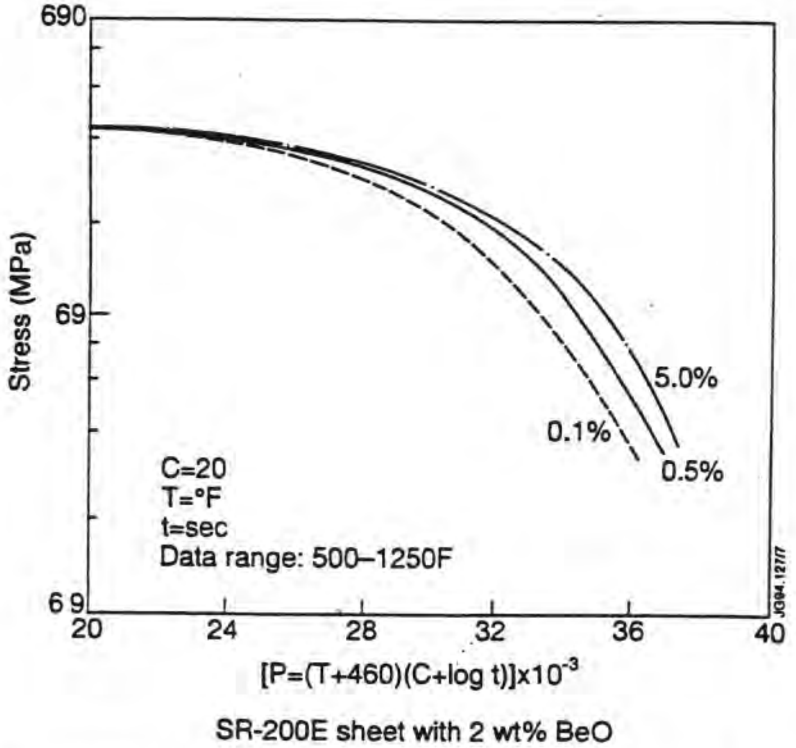
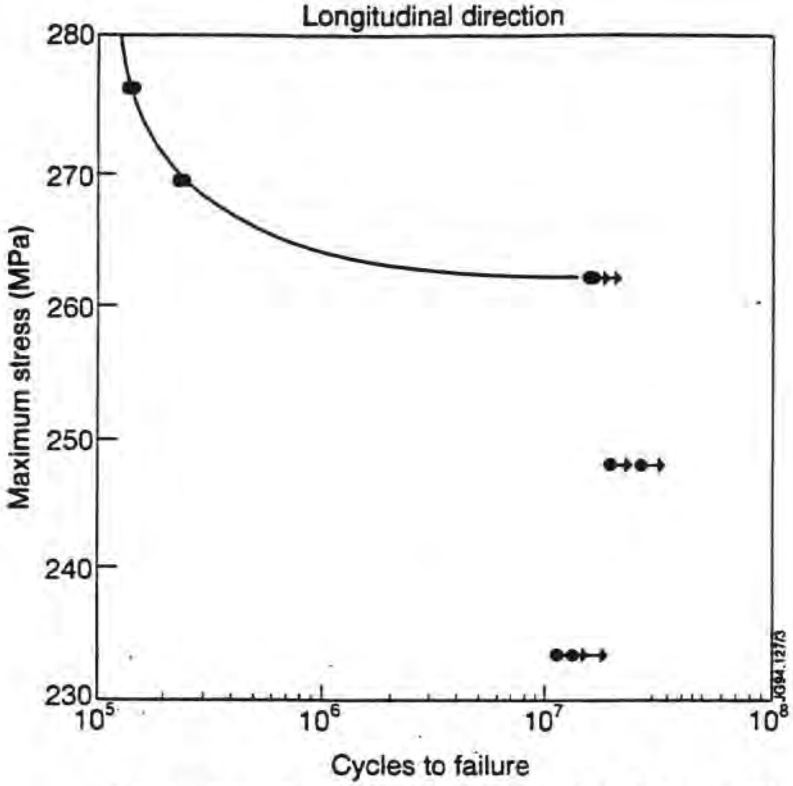
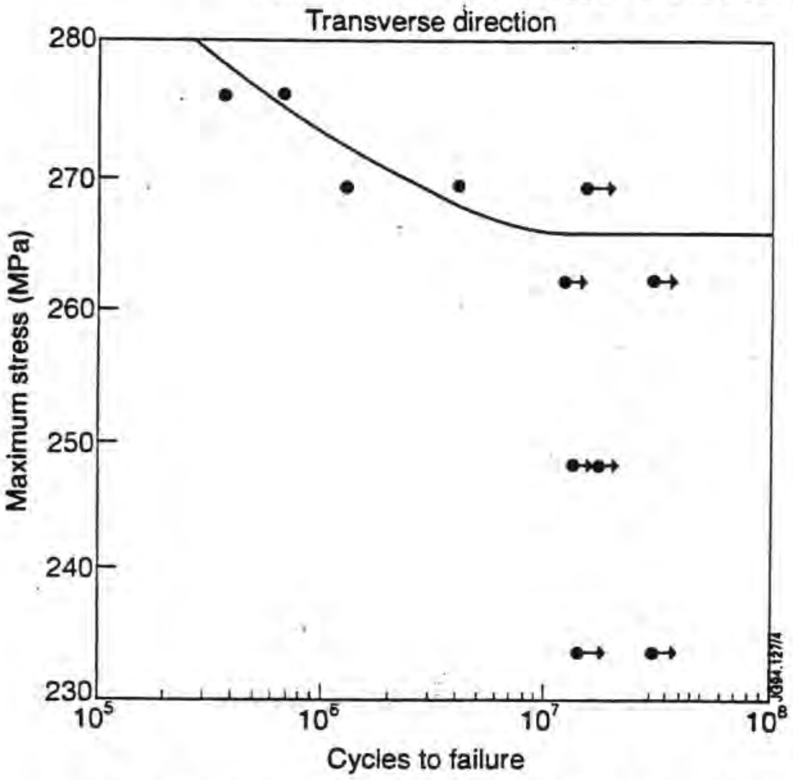


Fig. 28 Larson-Miller parameter versus stress for SR-200E PM Be sheet [36].



Smooth specimen, S200F VHP Be with 1.06 wt% BeO

Fig. 29 S/N curve for smooth specimen room temperature rotating beam fatigue data at R = -1 for S-200F VHP Be [19].



Smooth specimen, S200F VHP Be with 1.06 wt% BeO

Fig. 30 S/N curve for smooth specimen room temperature rotating beam fatigue data at R = -1 for S-200F VHP Be [19].

### 6n Fatigue

Haws [19] measured smooth room temperature fatigue for S-200F grade VHP Be with a Krouse rotating beam fatigue machine according to ASTM specification E-466. Transverse fatigue properties appear to be greater than longitudinal properties. Figures 29 and 30 show S/N curves for the longitudinal and transverse directions respectively. This data is for R values (ratio of minimum stress to maximum stress) of -1. Fatigue life ($10^7$ cycles) is 262 MPa and 266 MPa for the transverse and longitudinal directions respectively. The above tests are a case where the mean stress is zero.

### 6o Fracture Toughness

Fracture toughness testing is difficult in beryllium. The relatively brittle nature of the metal makes nucleation of a fatigue crack difficult using the ASTM E-399-83 standard. Fatigue cracks are successfully nucleated using compressive forces; a precracking stress ratio of $R < 0$ is successfully used rather than the value of +0.1 usually required by the ASTM standard. The ASTM fracture toughness committee E-24 now recommends in addendum A-2 to the ASTM E-399-83 standard a change in the testing procedure which would allow fatigue cracking to occur at up to 80% of the estimated $K_{IC}$ value with a negative stress ratio.

Grensing et al. [27] measured room temperature fracture toughness of VHP consolidated attrition ground powder (S-200E grade Be) having 1.1 wt% BeO, VHP impact ground powder (S-200F grade Be) having 0.67 wt% BeO and VHP consolidated atomised spherical powder (ASP) having 0.37 wt% BeO according to ASTM standard E399-83 using a stress ratio of $R = -2$. Lemon and Brown [45] report fracture toughness for VHP S-65 grade Be having 0.7 wt% BeO using a stress ratio of $R = -3$. Haws [37] measured fracture toughness according to ASTM-399 for multiple samples taken from a single production lot of S-200F grade beryllium using an unspecified stress ratio. Production data for S-200F-H, a HIP version of S-200F, has also been reported [46].

A summary of results at room temperature for different grades is shown in Table 10 below.

Table 10: Room Temperature Fracture Toughness for VHP Beryllium from Different Powder Sources

| Material | Specimen Orientation | Fracture Toughness $K_{IC}$ (MPa-m$^{-1/2}$) | Std. Deviation | n | % BeO | Grain Size (µm) | Reference |
|---|---|---|---|---|---|---|---|
| VHP S-200E | L-T | 9.85(1) | 0.363 | 11 | 1.7 | 8.4 | 44 |
| | T-L | 11.05(1) | 0.81 | 11 | | | |
| VHP S-200E | L-T | 10.3 | 0.468 | 5 | 1.1 | NA | 45 |
| | T-L | 12.3 | 0.230 | 3 | | | |
| VHP S-200F | L-T | 10.62 | - | 1 | 0.67 | 8.7 | 20 |
| | T-L | 12.31 | | 1 | | | |
| VHP S-200F | L-T | 9.5 | 0.28 | 3 | 1.06 | NA | 35 |
| | T-L | 10.9 | 0.38 | 4 | | | |
| VHP S-65 | L-T | 10.6 | 0.77 | 3 | 0.7 | 11.4 | 44 |
| | T-L | 10.9 | 0.72 | 3 | | | |
| VHP ASP2 | T-L | 13.59 | - | 1 | 0.37 | 13.2 | 20 |
| HIP S-200F-H | L-T | 9.07 | 0.41 | 3 | 0.78 | 7.2 | 46 |
| | T-L | 9.16 | 0.32 | 3 | | | |

(1). These are $K_q$ values because $K_{max} > 0.6K_{IC}$.
(2). Atomised Spherical Powder.

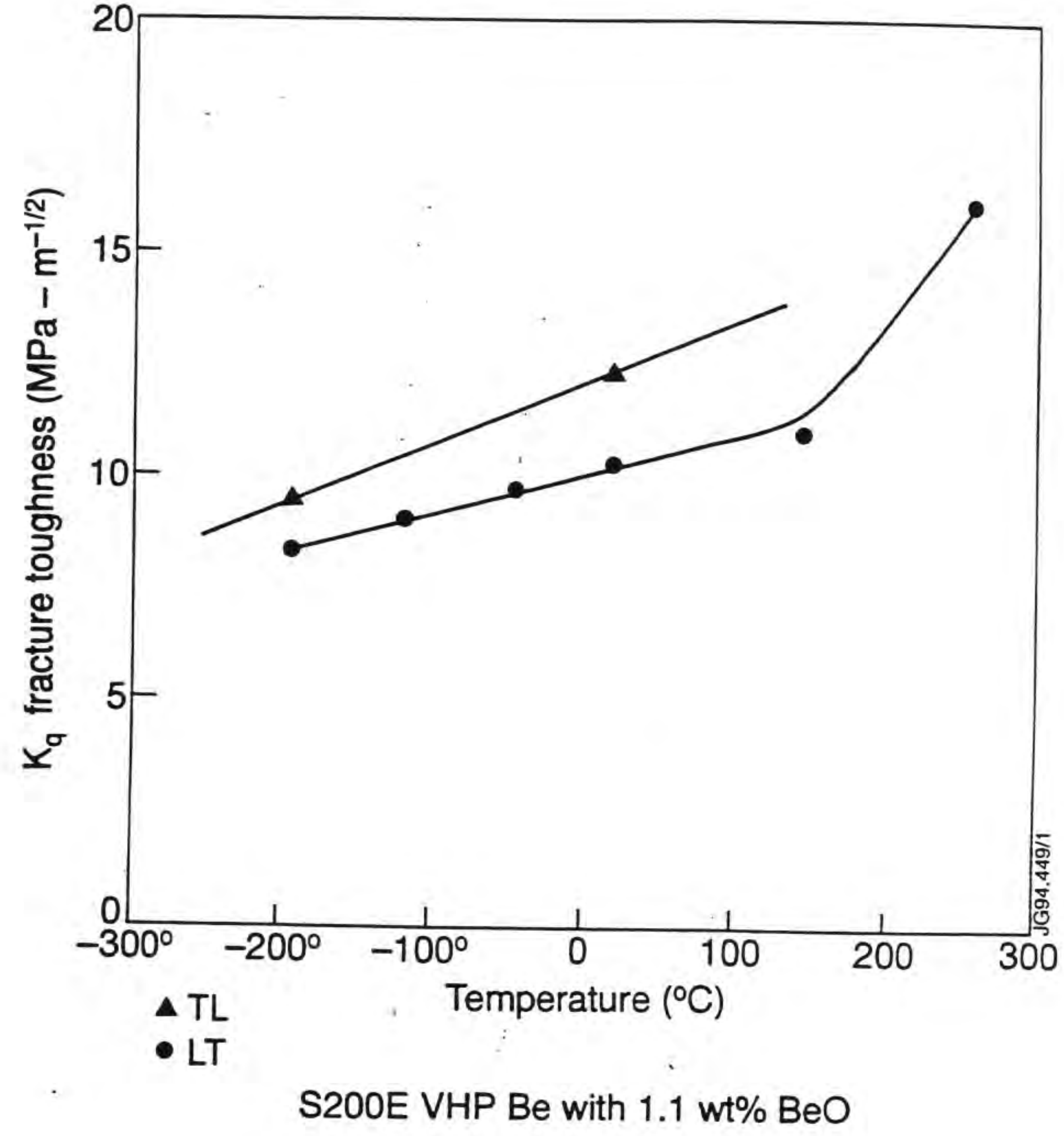


Fig. 31 Plane strain fracture toughness ($K_q$) for S-200E VHP Be [47].

Specimens labelled L-T were cut from a VHP billet so that the testing load was applied parallel to the longitudinal (L) or pressing direction, and the crack was propagated perpendicular to the pressing direction, transverse (T). In T-L specimens, the testing load was applied perpendicular or transverse (T) to the pressing direction, and the crack was propagated parallel to the pressing direction (L). Values for $K_{IC}$ range from 9.9 to 13.59 MPa-m$^{-1/2}$. S-200F exhibits a slight improvement in fracture toughness compared to S-200E. There is insufficient data to show whether atomised spherical powder material consistently shows better fracture toughness than the other grades. Further testing is warranted.

Figure 31 shows the general trend of plane strain fracture toughness versus temperature for S-200E grade beryllium [47]. This testing was done with compact tension specimens according to ASTM E-399-72 using a stress ratio of $R = -1$. Fracture toughness ranges from approximately 8 to 16 MPa-m$^{-1/2}$ as temperature increases from -200°C to + 200°C.

## 7. PROPERTIES AFTER NEUTRON IRRADIATION

The effects of neutron irradiation on the thermomechanical properties of beryllium are very difficult to summarise because testing to date has been done for widely differing combinations of irradiation conditions (flux, fluence, temperature, time), post irradiation testing conditions (temperature, pre-test annealing) and beryllium grades [48]. Often the forms of beryllium tested were non-commercial specimens made in the laboratory and not characterised in the unirradiated condition. Irradiation temperatures often differed substantially from temperatures of post irradiation testing, which makes extrapolation of the data to ITER operating conditions problematic. None of the tests were conducted with 14 MeV neutrons such as ITER will produce. However, there is expected to be an overlap in energy spectrum between fission test reactor neutron spectrum and the neutron spectrum produced by reflection of 14 MeV neutrons from the ITER stainless steel supporting structure, so testing in existing fission test reactors may provide valuable baseline data.

Qualitative trends for beryllium thermomechanical properties after fission test reactor irradiation have been summarised by Gelles [48]. Beryllium structure is altered during neutron irradiation by displacement damage and by transmutation. Displacement damage generates a wide range of defects in the beryllium crystal structure. High defect concentrations are also produced. Transmutation produces helium in the crystal structure which acts as defects and which produces swelling. The effect of defects and swelling on thermomechanical properties depends on the irradiation temperature and on the temperature during post irradiation testing. As noted above, widely differing combinations of these variables have been studied. The broad trends stated by Gelles generally refer to the highest of the two temperatures. At low temperatures (T < 400°C), defects from displacement damage and transmutation will block dislocation motion and thereby increase strength. Hardness follows the same trend as strength; the increase in hardness upon radiation is called radiation hardening. Percent elongation decreases upon irradiation at low temperature; this is called embrittlement. Fracture toughness is decreased by irradiation at low temperature. In general, increasing fluence (neutrons/cm$^2$) increases the effects on the above properties. However, once ductility has reached zero, strength will decrease with increasing fluence.

At high temperatures (T > 400°C), thermomechanical behaviour is a more complex function of fluence, time and temperature. The additional factors of defect annihilation, swelling of entrapped helium, and accumulation of helium as bubbles complicates behaviour as compared to low temperature irradiation. Gelles et al. state that above 280°C the functional dependence of strength on fluence may change from lower temperatures. Above 600°C there is considerable variation in the observed trends. Some data show decreases in strength with increased fluence and some data show increase in strength. There are generally less severe drops in percent elongation with increased fluence for T > 600°C.

It should be noted that the above results are largely for obsolete beryllium grades or beryllium manufactured in the laboratory. It is expected that commercial grades will perform much better [48]. This needs to be confirmed by experiment.

## 8. CHEMICAL PROPERTIES

Beryllium has a strong affinity for oxygen which is usually present in all forms of beryllium exposed to air in the form of BeO. In a tokamak edge plasma beryllium has been shown to getter oxygen strongly.

Hydrogen does not normally dissolve to any great extent in beryllium metal.

However, the redeposition of beryllium atoms from the edge plasma onto PFC surfaces results in a co-deposition of hydrogen with beryllium. For DT pulsed and steady state devices the amount of tritium atoms trapped this way are crucial in respect of tritium inventory and accountability. For a burning DT fusion reactor precise data for this chemical/physical process would have a strong impact on the tritium handling system.

The flammability of beryllium, in particular porous beryllium under accident conditions where upon hot beryllium is exposed to air or a steam air mixture have been investigated [49, 50]. The types of beryllium used are not commercial grades of interest to fusion applications. Evidently these tests must be repeated using modern forms of Be. Mitigation of the risk of this accident scenario is evidently a system design problem.

Reactivity of beryllium with liquid metals such as sodium, potassium and lithium is low below 500° provided that the oxygen concentration of the metals is low [13]. Beryllium is attacked by hydrofluoric acid, hydrochloric acid, and alkali hydroxide solutions. It has acceptable corrosion properties in high purity cooling water at 100°C in the pH range 5.5 to 6.5, and has been used in that environment for over ten years in the Materials Testing Reactor [51]. In addition to high reactivity with oxygen, beryllium will react with carbon based materials to form beryllium carbide at temperatures as low as 750°C. Beryllium reacts with most refractory metals e.g. tungsten to form intermetallic compounds.

## 9. SUMMARY OF CHARACTERISATION NEEDS FOR PFC APPLICATIONS

The need of additonal characterisation of beryllium properties is coupled to the choice of operational scenarios for ITER and second to the level of analysis intended for design of PFC's. The ITER operational scenario has variously been described as 100-600°C and 100°C melting of the outer beryllium layers. Characterisation needs are respectively rather minimal or very extreme. This refers to unirradiated properties. There is insufficient data on radiation damage to beryllium.

The level of data available for most structural and other grades of beryllium is adequate for a decision to be made between the relevance of various grades to a design problem. Substantial additional characterisation is mandatory if it is intended to assess analytically lifetime of PFC's or analyse observed failure/fatigue of prototypes.

### 9a Unirradiated Properties

The design of JET PFC and associated material development was based on prototypical tests, e.g. [5], [21]. The substantial thermomechanical database for various products based on S65 powders is a consequence, i.e. [21], [41]. Nevertheless some further work needs to be done for this grade of beryllium as well as for other grades.

Thermal conductivity versus temperature has been measured extensively yet needs to be more specifically defined for modern VHP grades.

The coefficient of thermal expansion (CTE) of block grades needs to be accurately measured over the whole temperature range of interest for fusion applications. Measurements of CTE for both VHP and HIP grades would be beneficial.

Electrical resistivity of block materials needs to be measured over the whole temperature range of interest for fusion applications. This needs to be done for grades with different impurity levels.

The temperature dependence of elastic modulus is described with a few data points. Additional data points may be needed.

Shear modulus needs to be measured as a function of temperature for modern beryllium grades.

There is significant scatter in room temperature Poisson's ratio and no definitive measurement of temperature dependence of this property. Thorough and precise characterisation is needed for practically all grades of beryllium.

Design of PFC may require precise stress versus strain curves for temperatures up to 1200°C. Characterisation of several grades with different Be0 contents would be most useful. The relevant strain rates would also need to be considered.

Although there is sufficient data to see the trends of tensile properties with temperature, there is no complete coverage of the temperature range for all modern grades. There is a good data set for IM sheet, and for VMP S-65 grade. It would be useful to obtain more data for S-65 grade, as it is the baseline grade for ITER. However, the above data is for aerospace relevant strain rates. A characterisation program using strain rates relevant to fusion is desirable.

There is a lack of <u>systematic creep data</u> and <u>high temperature fatigue data</u> for all beryllium grades presently in production. This may be one of the most critical deficiencies in the database, since beryllium will definitely be subjected to thermal cycles and has a design steady state operating temperature of 600°C.

A complete set of data is needed on the temperature dependence of <u>fracture toughness</u>, particularly for the S-65 grade. It is not possible to generate valid $K_{IC}$ for sheet, but $K_q$ values can be measured.

### 9b Irradiated Properties

As discussed above in section 7 a complete set of property measurements of neutron irradiated commercial grade material is needed. This is the area of greatest need. The most critical properties are high temperature creep and thermal fatigue. Many authors e.g. Gelles [48] have suggested that optimizing Be for strength under unirradiated conditions may not be possible while simultaneously optimizing for high temperature resistance to radiation damage. In fact the authors know of no published data on the susceptibility of modern forms of beryllium to a well characterised thermal neutron fluence let alone to even a very low fluence of fast neutrons. Given that in a fusion reactor such as ITER thermal neutrons will certainly be present together with fast neutrons, it seems advisable to carry out measurements on specimens that are irradiated by thermal neutrons. The authors are aware of substantial efforts being made in this area. The database in this aspect of beryllium properties is as yet extremely sparse.

There is a critical need for a thorough, systematic characterisation of thermomechanical properties for commercial beryllium grades after neutron irradiation under ITER relevant fluxes, fluence and temperature. As noted above, no facilities exist for irradiation with the 14 MeV neutrons which will be produced in ITER. A characterisation program using existing fission test reactors would provide baseline data. Although previous characterisation emphasised tensile and compressive strength testing, the ITER programme should include all the other thermomechanical properties in particular data on high temperature fatigue and creep.

The present use foreseen for beryllium is in the form of cladding. Swelling and embrittlement due to neutron irradiation are likely to be of great concern as one likely outcome would be flaking of coatings and delamination of cladding. These factors are likely to be important limitations on the life time of beryllium PFCs.

### 9c Ductile Beryllium

The choice of beryllium grades by JET has been dictated by consideration of high temperature strength, ductility at 300°C and levels of high Z impurities. Fabrication techniques were developed to give several tons of materials with reproducible minimum properties. Clearly this grade has been chosen as a reference for ITER. Further developments for ITER have been foreseen to produce grades with maximum realistic ductility at low temperatures, i.e. 25-100°C. There were some references in the late 70's to a form of beryllium which had 10% elongation in three orthogonal directions [52] at room temperature, so-called "ductile beryllium" [14], [53], [54]. A wealth of scientific data shows this result to be improbable.

A single crystal of beryllium will have very different mechanical properties depending on which crystallographic direction is tested. Ductility of beryllium single crystal is virtually zero parallel to the crystallographic "c" axis. The limiting factor, therefore, in beryllium ductility is the ease of cleavage of the basal plane in the hcp structure. Stresses perpendicular to the basal planes are reduced by slip and cause cleavage.

Early work in the 60's and 70's was able to achieve ductility increases in beryllium products from 1% min. (2% typical) to the current 3% (4-5% typical) by a combination of lower oxide content, finer grain size and impurity control. Such improvements, unfortunately, have their limits since they are essentially second order effects rather than fundamental solid state changes. Selected beryllium products with 4% min. ductility may be available in the near term (at added expense) from current products. Further substantial increases in room temperature isotropic ductility are unlikely in a commercially feasible product from; i.e., it is unlikely that so-called ductile beryllium can ever be produced.

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## APPENDIX A

## JET SAFETY EXPERIENCE

The principal hazard arising from the use of beryllium is injury or disease following the inhalation of beryllium dust or dust comprising various beryllium compounds. It is noted that beryllium oxide is used industrially due to its refractory properties (melting point 2570°C) and that safe handling procedures for beryllium and for components contaminated by beryllium/beryllium compound dust have been instigated in various manufacturing and research establishments. JET has had the most exhaustive experience in the use of PFC for fusion and the various handling procedures developed there are herein reported.

The internal surfaces of JET have been contaminated with beryllium either evaporated for density control or as a result of localised melting due to high heat loads. An extensive programme of safety has been successfully implemented on JET [1] based on WHO recommendations and UK Health and Safety Regulations [2].

JET practice is to limit the maximum airborne contamination due to beryllium to a beryllium-worker in a controlled access area without protection to 0.2 $\mu gm/m^3$ (1/10th the industrial standard of 2 $\mu gm/m^3$). Similarly surface contamination levels of 10 $\mu g/m^2$ are the maximum allowed (vs 100 $\mu gm/m^2$ industrial standard). The presence of beryllium either in the form of airborne dust or as surface contamination is detected by analysing filter or smear samples by the atomic absorption spectroscopic method. JET also has used laser induced emission spectroscopy as a detector for the presence of airborne beryllium dust without relying upon this method to determine concentrations.

JET has now had two major and lengthy interventions to the beryllium contaminated vacuum vessel, the most recent one lasting nearly two years. During the latter operation decontamination has reduced initial airborne beryllium concentration from values of up to $10^4$ $\mu gm/m^3$ which required working in full biological protection suits to values which allow working without dust masks. For further details of the aggressive decontamination methods required to achieve this see Scott et al. [3].

It is felt by the authors of this review that safe working practices based upon the JET experience can readily be developed for any controlled fusion experiment to work with beryllium PFC's provided sufficient care is taken in demarcating those areas of the device and of supporting laboratory that require special attention. In any experiment using DT for ignition studies and/or to investigate the burning of a DT plasma, tritium safety related issues and the need for handling irradiated components are likely to predominate in how safe working practice is to be implemented even allowing for remote handling of the most severely activated parts.

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Note:
Handling Aluminum-Beryllium Alloys in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals.

The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material.

For additional information on safe handling practices or technical data on Aluminum Beryllium Alloys, contact Brush Wellman Inc.